# DECISION SUPPORT SYSTEM DEVELOPMENT FOR HUMAN EXTRAVEHICULAR ACTIVITY

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Matthew James Miller

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**DECISION SUPPORT SYSTEM DEVELOPMENT FOR HUMAN EXTRAVEHICULAR ACTIVITY**

Approved by:

Dr. Karen M. Feigh, Adviser
School of Aerospace Engineering
*Georgia Institute of Technology*

Dr. Amy R. Pritchett
School of Aerospace Engineering
*Georgia Institute of Technology*

Dr. David A. Spencer
School of Aerospace Engineering
*Georgia Institute of Technology*

Dr. Ute M. Fischer
School of Literature, Media, & Communication
*Georgia Institute of Technology*

Dr. Kerry M. McGuire
NASA Fellowship Mentor
Space Human Factors
*NASA Johnson Space Center*

Date Approved: August 14, 2017

*Scientists discover the world that exists;*

*engineers create the world that never was.*

*— Theodore von Kármán*

To Anna, Addie, and my family

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## SUMMARY

The design and development processes for decision support systems (DSS) can have important implications for yielding desirable and effective design solutions. This dissertation seeks to understand, and ultimately provide a meaningful pathway to generating useful decision support system designs for use in environments that do not yet exist (e.g. envisioned worlds). The contributions of this thesis are two fold. The first is domain specific and addresses the known deficiencies that will impact future human extravehicular operations. The second is methodological and generalizable across many domains. Central to this effort is realizing that design requirements are the medium through which hypothesized system designs are built. This dissertation first demonstrates that cognitive systems engineering (CSE) methods can be applied to yield design insight in the form of high level design requirements amenable to traditional systems engineering processes (Chapter 3). Second, this dissertation demonstrates how a subset of those requirements, along side envisioning and testing within a future work context, can yield prototype designs suitable for supporting future extravehicular activity (EVA) operations (Chapter 4 and 5). Finally, this dissertation evaluated the resultant prototypes against the requirements to demonstrate both validity of the requirements and the verification of the design (Chapter 6). The intent here is to first define what is required by the domain and hypothesis how new design solutions might be capable to promote desired capabilities specified by the requirements derived from the work in Chapter 3. As a result, this thesis contributes the underlying science needed to design a DSS within the EVA work domain for future mission operations.

# CHAPTER 1

# INTRODUCTION AND MOTIVATION

Human spaceflight is arguably one of humankind's most challenging engineering feats, requiring carefully crafted synergy between human and technological capabilities. One particular component of human spaceflight pertains to the activities conducted outside the safe confines of the spacecraft, known as extravehicular activity (EVA). Since the egress of astronaut Ed White on June 3, 1965 during Gemini IV, NASA has advanced EVA capability through a series of flagship programs which included Gemini, Apollo, Skylab, Shuttle and the International Space Station (ISS). The past five decades of human spaceflight have established EVA as a mission critical capability with a proven track record in spacecraft and payload inspection, repair, and construction (Portree and Treviño, 1997).

Despite the prior successes of EVA, current operational practices are likely unstable for future NASA missions, with new missions demanding more frequency and a variety of new operational environments (Ano, 2009b,a). NASA is employing a flexible pathways approach, as shown in Figure 1.1, to guide the future of human spaceflight (Augustine et al., 2009; Korsmeyer et al., 2010). The near-term possible destinations include the moon, near-Earth objects (NEOs), and Mars. While each destination presents a unique set of technological challenges, one new constraint will become commonplace: time-delay associated with the vast distances the messages must travel to reach mission control located on Earth. For the Moon, time-delay is only on the order of seconds, but for NEOs and eventually Mars, time delays on the order of minutes to tens of minutes will exist as shown in Table 1.1.

This time-delay raises a fundamental issue that must be addressed: how might the spaceflight domain need to shift to accommodate future operations in the presence of time-delayed communication? For the entire history of human spaceflight, astronauts have

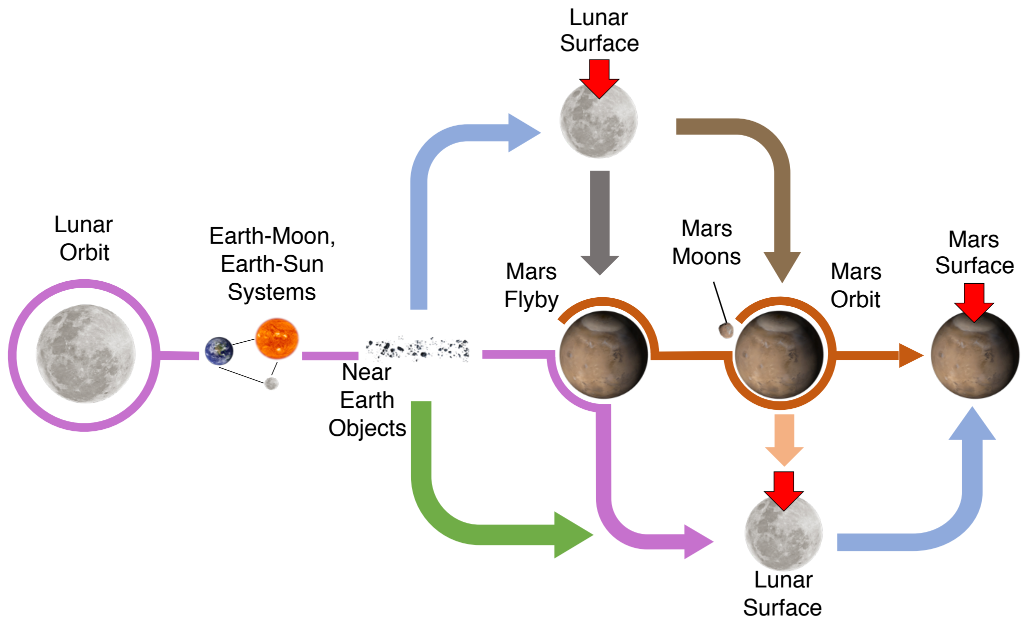


Figure 1.1: NASA's Flexible Path Destinations (Augustine et al., 2009).

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Table 1.1: Human spaceflight destinations, approximate distance from Earth, and approximate one-way light time delay.

| Destination | Lunar | NEOs (Lunar DRO) | Mars | |
|---|---|---|---|---|
| | | | Close | Opposition |
| Distance from Earth, km | 3.84E+05 | Variable | 5.57E+07 | 4.01E+08 |
| One-Way Time Delay, min | 1.3 sec | Variable | 3.1 | 22.3 |
| Mission Duration, days | Variable | 20-30 | 895-950 | |
| Reference | (Drake et al., 2010) | (Lopez et al., 2014) | (Drake et al., 2010) | |

worked alongside ground support personnel and support systems using *real-time* communication to facilitate and ensure mission success. Deep-space destinations will ultimately preclude the natural dialog, processes, and overall spaceflight architecture the domain is currently accustomed to. Therefore systemic, structural shifts in the domain of human spaceflight operations will need to occur. As part of this recognized shift, there is growing interest in developing technological systems to ensure mission success in a time-delayed communication environments (Frank et al., 2013; Marquez et al., 2013a; Holden et al., 2013; Smith et al., 2014; Shafto et al., 2012; Major et al., 2010).

However, questions still remain such as those stated below regarding how to best implement these new technologies.

- What is the appropriate allocation of functions between flight crew, ground crew and support systems?
- Which activities and roles should a new support system aim to support?
- How should the time sequencing of activities and events be supported in a time-delayed communication environment?
- How should the human and the support system interact?

As stated in the NASA's Draft of Modeling, Simulation, Information Technology and Processing for Technology Area 11, decision support systems (DSSs) are recognized as a *game-changing technology* for Human-System Performance Modeling (Shafto et al., 2012). DSSs could enable crew members to identify, diagnose, and recover from time critical irregularities during EVA without relying on real-time ground support. These skills will prove useful in a deep-space environment where mission control can no longer provide near instant response and direction when system anomalies arise (Drake et al., 2010; Marquez et al., 2013a; Holden et al., 2013). In an era where technology can provide an overabundance of data, DSS development is critical to the handling and integration of that data into a useful informative platform for human explorers (Endsley, 2000).

**Given the critical role EVA will play in future deep-space operations, this thesis will focus on building a DSS for the subset of spaceflight activities related to EVA operations to enable more autonomous operations of the flight crew.** Currently, the EVA work domain is prescriptive, meaning that all activities are accompanied by detailed procedures outlining all required actions. Extensive training is required to prepare for issues that may arise during an EVA (Bell et al., 2006). The successful execution of EVA requires significant effort undertaken by astronauts (e.g. the flight crew) and the personnel that support all aspects of EVA from the ground (e.g. personnel located in Mission Control Center (MCC)). These support personnel are known as EVA flight controllers and they strive to manage the flight crew, the EVA timeline, and all associated hardware. They oversee all pre-planning, day-of, and post EVA operations and support off-nominal events such as hardware malfunctions, unscheduled task difficulties, and crew health variations. When an unanticipated event occurs, mission control acts in a real-time manner to mitigate deviations from nominal operations. In the presence of time-delayed communication, changes to the EVA systems and spacecraft will not be immediately available to mission control resulting in differential knowledge and understanding between the on-board crew and mission control. Thus, there exists a need to shift expert knowledge and decision making capability, in some capacity, from mission control to the flight crew to enable future EVA operations (Caldwell, 2000).

The consequences of time-delayed communication pose a unique set of challenges such as an impaired ability to provide relevant information, slow response to events and reduced situation awareness (Love and Reagan, 2013). Recent research programs have begun to investigate new communication protocols and modes of communication within time-delayed environments (Fischer et al., 2013; Frank et al., 2013; Fischer and Mosier, 2014; Frank et al., 2015; Stetson et al., 2015). However, results from these preliminary studies indicated that novel support tools can both increase and decrease operator workload, depending on the specific operator and test condition. In another human-in-the-loop simulation, Fischer and Mosier (2014) found that teams took significantly longer to repair system failures when operating under time-delayed communication and that adapting to the communication medium itself is key to establish shared task understanding. So while new support systems appear to be a logical solution to supporting future operations, it is not clear how to best design technological solutions.

The first step towards addressing these challenges is properly defining the appropriate system and its boundaries. The EVA work domain can be described as a complex sociotechnical system (Vicente, 1999) and has the following characteristics:

- **Large Problem Space**: many variables to take into account

- **Social**: communication plays a vital role between the many specialized individuals
- **Heterogeneous**: many contributing perspectives and experience levels
- **Distributed**: operators within the EVA work domain are dispersed geographically
- **Dynamic**: many technical systems requiring a lot of anticipation on how the systems will behave
- **High Risk**: any errors could potentially result in loss of hardware or life of the flight crew
- **Coupled**: many technical systems results in possible unpredictable interactions and consequences
- **Automated**: high degree of automation for many of the subsystems
- **Uncertain**: flight controllers act as problem solvers with possible incomplete information
- **Mediated Interaction**: use of devices and personnel to assess and utilizes systems

Taking a sociotechnical view of EVA operations provides an opportunity to not only address the more commonly known engineering challenges, but also to incorporate human and organizational considerations within the process of designing a support system. There are many dimensions to consider and a clear picture of DSS purpose is currently lacking for future EVA operations. This is due, in large part, to the traditional engineering research that exists within the EVA literature whose purpose is to simply keep a human alive in the vacuum of space. In the modern era where technology affords an incredible amount of capability, the real challenge is to adequately identify the necessary versus superficial capabilities worth developing.

I propose that starting from this broad perspective will enable a more appropriate and meaningful tailoring of DSS design specifications. However, the incorporation of these perspectives into actionable design insight can be challenging. At the core of traditional systems engineering (SE), requirements are defined by customer and user needs from relevant stakeholders at the onset of the project. But the intent here is to design future systems in a future context, of which there are no experienced stakeholders or a even clear understanding of customer needs. Furthermore, the sociotechnical perspectives derived by traditional SE methods (e.g. stakeholder interviews, observations) are oftentimes ill-defined, assumed, or ignored, leaving a high degree of uncertainty in the system design (Militello et al., 2009). Therefore, approaches that incorporate sociotechnical perspectives such as those from the cognitive systems engineering (CSE) community must be leveraged and integrated with the systems design process to offer design guidance. However, existing deficiencies within the CSE methods such as appropriate mechanisms that can be readily incorporated and requirements specificity amenable to the SE process must be addressed.

The contributions of this thesis are two fold. The first is domain specific and addresses the known deficiencies that will impact future human EVA operations. The second is methodological and generalizable across many domains. Central to this effort is realizing that design requirements are the medium through which hypothesized system designs are built. Therefore, I demonstrate that CSE methods can be applied to yield design insight in the form of high level design requirements amenable to traditional SE. Furthermore, I demonstrate how a subset of those requirements, along side envisioning and testing within a future work context, can yield prototype designs suitable for supporting future EVA operations. As a result, this thesis contributes the underlying science needed to design a DSS within the EVA work domain for future mission operations.

## 1.1 Dissertation Overview

There are 7 chapters in this dissertation including this introduction as shown in Table 1.2. Chapter 2 provides the necessary background to understand the perspectives, approaches, and contributions of this dissertation. Topics covered include the application and methodology of cognitive work analysis (CWA), considerations of the envisioned world problem, a brief review of decision support systems and their applications, and a review of the current state of EVA research. Chapter 3 demonstrates the application of the first two phases

Table 1.2: Dissertation outline.

| Chapter | Title |
|---|---|
| Chapter 1 | Introduction and Motivation |
| Chapter 2 | Literature Review |
| Chapter 3 | Cognitive Work Analysis of the EVA Work Domain |
| Chapter 4 | EVA DSS Prototype Development |
| Chapter 5 | EVA Decision Support System Assessment |
| Chapter 6 | Experiment Results and Discussion |
| Chapter 7 | Conclusion and Future Research Directions |

of CWA to the EVA work domain. The CWA models show an incremental derivation of DSS design purpose and result in the formulation of DSS design requirements. Chapter 4 describes the resulting DSS prototype designs. Chapter 5 provides a description of how NASA analog research programs were leveraged to both derive a detailed view of the prototype designs as well as develop the spartan laboratory simulation environment. Chapter 6 provides the results of the simulation that evaluates the prototype designs in a relevant simulation environment. Finally, Chapter 7 summarizes the contributions of this research and provides directions for future research.

# CHAPTER 2

# LITERATURE REVIEW

The concept of 'design' is rooted in a multitude of disciplines and perspectives. This thesis, however, focuses on the insights afforded by a specific field of research known as cognitive systems engineering (CSE) which incorporates "a realistic model of how the human functions cognitively (Hollnagel and Woods, 1983, p. 586)" in the design process of complex sociotechnical systems. Specifically, the CSE framework, known as cognitive work analysis (CWA), is applied in this work to the design process of a decision support system (DSS) for future human spaceflight operations - that have yet to be fully realized in the exiting work domain. This thesis leverages CWA to understand the cognitive demands within an existing EVA work domain and applies that insight to the design of a DSS applicable to future EVA operations.

Before beginning, it is important to touch on the prior applications of CWA as well as highlight the challenges this thesis aims to address. Sections 2.1 and 2.2 of this chapter introduces the concepts of CWA and the *envisioned world problem*; detailing the benefits and current limitations that exist within this field of research. Section 2.3 introduces the concepts of a decision support system and the potential impacts it can have on system performance. Section 2.4 reviews the domain of application (human extravehicular activity) and summarizes the current state of research within this work domain. Finally, a brief comment on the methodological approach adopted for this thesis is described in Section 2.5 and the contributions of this thesis are provided in Section 2.6.

## 2.1 Cognitive Systems Engineering Impact on Design

### 2.1.1 CSE Definitions and Case Studies

Cognitive systems engineering is defined for this thesis as stated below:

> **Definition: Cognitive Systems Engineering**
> Cognitive Systems Engineering is an approach to the design of technology, training, and processes intended to manage cognitive complexity in a sociotechnical system (Militello et al., 2009, p. 263)

Two key terms in this definition establish the core elements of CSE: *sociotechnical system* and the *complexity*. Sociotechnical systems are multifaceted, consisting of technical, psychological, and social elements (Vicente, 1999). As technological capabilities increase, designers' ability to appropriately apply those technologies within increasingly complex sociotechnical domains will require a deep understanding of the interaction between people and the organizational structures they operate within (the social system) and the technologies (the technical systems) they utilize to successfully achieve overall system goals and objectives. These systems involve context-rich workplace settings, organizational structure, human operators, and sophisticated technology that when taken collectively are known as complex sociotechnical systems (Baxter and Sommerville, 2011; Walker et al., 2008; Waterson et al., 2015). Complexity in this context stems from a plethora of sources such as human information processing and problem solving [see Roth et al. (2010)] and the multidimensional aspects inherent to complex sociotechnical systems as shown in Table 2.3 [see Vicente (1999)].

Cognitive work analysis (CWA) has emerged as a promising CSE framework to understand these types of systems and cope with the stated dimensions of complexity (Rasmussen et al., 1994; Vicente, 1999). CWA establishes the characteristics of the work domain and describes ***how work can be done*** rather than ***how work is done or should be done*** (Vicente, 1999). This is accomplished by identifying the characteristics that serve to influence

Table 2.1: Dimensions of complexity of sociotechnical systems as defined by Crone et al. (2003); Vicente (1999).

| Complexity Characteristic | Description |
|---|---|
| Large problem space | Complex systems have a high number of variables that interact with each other. This interaction tends to be complex and not easily quantified. |
| Social | The number of people involved with the system determines whether the system is complex or simple. The larger the number of people, the more complex the system because factors such as communication play a major part in how well a system performs. |
| Heterogeneous perspective | The degree of variation in factors such as the background, values and views of the workers/ users of the system will alter the degree of complexity of the system because outcomes, for example, reaching consensus, may be more difficult to achieve. |
| Distributed | The social coordination may be hampered by both geographical location and cultural aspects of the personnel involved in the design of the system. |
| Dynamic | Systems that are complex often show a high degree of dynamic behaviour with long response times. This means that for an outcome to be successful, personnel will have to anticipate the results of their actions well before the result of the action is seen. |
| Hazard | An error made in operation of a complex system could result in a catastrophic result. |
| Coupling | Complex systems exhibit a high degree of interaction between sub-systems thus making it difficult to predict the overall behaviour of the system. |
| Automation | A high degree of automation is characteristic of complex systems. In complex systems the worker/ operator who monitors the system is expected to intervene quickly and decisively to overcome abnormal situations that tend to be infrequent. The intervention is generally cognitive rather than psychomotor. |
| Uncertainty | Complex systems tend to present an incomplete picture of what is actually happening this may be due to failure of sensors, random drift or a real change in the system. Hence, workers will need to act as problem solvers with possibly impoverished data. |
| Mediated interaction | Users of the system may get their view of the system (or world) from a device and may need to bring to bear significant cognitive resources to make sense of what is being viewed. |
| Disturbances | Complex systems tend to exhibit behaviour that may occur infrequently and be unanticipated by the designers. Workers are then expected to understand what the behaviour means and act to bring the system back to operating within normal conditions. |

Table 2.2: Cognitive work analysis phases as defined by Vicente (1999).

| Analysis Phase | Types of constraints or boundaries |
|---|---|
| Work Domain Analysis (WDA) | Purposes, values and priorities, functions, and physical resources |
| Control Task Analysis (ConTA) | Activity in terms of work situations, work functions, and control tasks |
| Strategies Analysis (SA) | Strategies for carrying out activity |
| Social Organization and Cooperation Analysis (SOCA) | Distribution of work including allocation of work to individuals; organization of individuals into teams; and communication requirements |
| Worker Competencies Analysis (WCA) | Perceptual and cognitive capabilities of workers |

the cognitive and collaborative performance of the domain operators. CWA incrementally identifies the constraints of a sociotechnical system through a series of analysis phases described in Table 2.2 as a means to yield effective designs.

CWA has been applied in numerous fields such as aviation (Naikar et al., 2005, 2006; Sanderson and Naikar, 1999; Dinadis and Vicente, 1999; Naikar et al., 2003; van Dam et al., 2008), military command and control (Bisantz et al., 2003; Jenkins et al., 2008a; Burns et al., 2005, 2009; Jenkins et al., 2008b; Lintern, 2005; Chalmers and Lamoureux, 2005; Cummings, 2004), nuclear power plant operations (Burns, 2007; Burns et al., 2003; Lau et al., 2008; Itoh et al., 1995), and health care (Sharp and Helmicki, 1998; Miller et al., 2009; Watson and Sanderson, 2007; Ashoori and Burns, 2013; Jiancaro et al., 2013). A recent review by Read et al. (2012) concluded that CWA is widely regarded as a useful tool for interface design by identifying 53 unique research efforts demonstrating CWA for interface design and 6 studies dedicated to function allocation purposes. Additionally, most of the research efforts performed to-date have only used selected analysis phases of the CWA framework. A subset of these studies is shown in Table 2.3, where the predominate analysis techniques implemented are the work domain analysis (WDA) and control task analysis (ConTA) phases. For more expansive reviews of the applications of CWA, see McIlroy and Stanton (2015) and Jiancaro et al. (2013). As a result of these applications, WDA and

ConTA are mature modeling tools of the CWA framework that can be implemented in this thesis and are described in Chapter 3.

### 2.1.2 Benefits and Limitations of CSE

Cognitive Work Analysis is an established framework for informing system design. As summarized by Bisantz and Roth (2008, p. 31), CWA offers a way to "characterize the constraints that define the cognitive requirements and challenges, and the knowledge, skills, and strategies that underlie both expert performance and the error-vulnerable performance of domain practitioners." Nonetheless, limited extensions of CWA insight has been made within the broader systems engineering (SE) design process.

The proposition that traditional SE processes and CSE insight should be more seamlessly integrated is not new. Pew and Mavor (2007) detailed a comprehensive assessment of the opportunities to integrate CSE perspectives with traditional SE processes. The Committee on Human-System Design Support for Changing Technology in the National Research Council emphasized that the "definition of user requirements should begin when the system is first being conceived, and those requirements should continue to provide important evaluation criteria right up to the time the system is placed in use (Pew and Mavor, 2007, p. 296)." In response to the committee report, the Journal of Cognitive Engineering and Decision Making issued a special issue dedicated to the specific mechanisms by which CSE methodologies could be synchronized with standard SE processes (Roth and Pew, 2008). Notably, Elm et al. (2008) proposed four key integration points, as shown in Figure 2.1, within the standard V-model of SE. The four integration phases included concept refinement, software development, testing, and post-system development. Within the early concept stage:

> "CSE is ideally suited to be the key breakthrough in the development of good system requirements because of its focus on overall system goals and the associated cognitive work (including coordination) that needs to be accomplished

Table 2.3: Recent applications of CWA to various complex sociotechnical work domains. AH: abstraction hierarchy; ADS: abstract decomposition space; DL: decision ladder; SRK: skills, rules, knowledge; TC-CTA: temporal coordination control task analysis.

| Work Domain | Citation | Application Description | CWA Analysis Phases WDA | ConTA | SA | SOCA | WCA | Analytic Products | Data Collection Methods |
|---|---|---|---|---|---|---|---|---|---|
| Aviation | Naikar et al. (2005, 2006) | Crewing concepts for Airborne Early Warning and Control aircraft | X | | | | | ADS | Observation; Interviews with SMEs using walkthroughs; Table top analysis; Critical decision method; Document analysis |
| | Sanderson and Naikar (1999) | Crewing concepts for Airborne Early Warning & Control aircraft | | X | | | | TC-CTA | Semi-structured interview; Document analysis |
| | Dinadis & Vicente (1999) | Military aviation (fuel and engine function) | X | | | | | AH; SRK taxonomy | Document analysis |
| | Naikar & Saunders (2003) | Pilot training | | X | | | | DL | Critical decision method interviews; Document analysis |
| | Van Dam, Mulder & van Paassen (2008) | On-board pilot support system | X | | | | | AH | Document analysis |
| Military Command and Control | Bizantz et al. (2003, 2001) | Information requirements fo rnext generation US Navy Surface combatant | X | X | | | | AH, DL, and mapping matrices | Semi-structured interview; Document analysis |
| | Jenkins et al (2008) | Command and control system for the army | X | X | X | X | | AH, ADS, Contextual activity template | Semi-structured interview using walkthroughs; SME meetings |
| | Burns, Bryant, & Chalmers (2005) | Naval command and control | X | | | | | AH | Document analysis, observations and SME interviews |
| | Burns, Torenvliet, Chalmers & Scott (2009) | Maritime tactical picture compilation | X | X | X | | | ADS | Document analysis; SME interviews |
| | Jenkins, Stanton, Walker, Salmon & Young (2008) | Command and control microworld | X | X | X | X | X | AH, ADS, DL, Contextual activity template, Strategies analysis | SME interviews; document analysis |
| | Lintern (2006) | Military analysis | X | | | | | ADS | Document analysis; Interviews with SMEs |
| | Chalmers & Lamoureux (2005) | Shipboard command and control | X | X | | | | ADS, DL | Document analysis; Cognitive walkthrough with SMEs |
| | Cummings (2004) | Missile retargeting | X | X | X | X | X | ADS, AH, DL, Information flow map | SME interviews; Simulation |
| Nuclear Power Plant Operations | Burns (2000) | Simulated power plant | X | | | | | ADS | Document analysis; Field study |
| | Burns, Kuo & Ng (2003) | Network management | X | | | | | ADS | Document analysis; Field study |
| | Itoh, Sakuma & Monta (1995) | Nuclear power | X | | | | | AH, SRK taxonomy | Document analysis |
| | Lau et al (2008) | Nuclear reactor plant | X | | | | | AH, SRK taxonomy, ADS | Document analysis |
| Health Care | Sharp & Helmicki (1998) | Neonatal intensive care | X | | | | | AH | Experimental field study |
| | Miller, Scheinkestel & Steele (2009) | Intensive care | X | | | | | AH | Experimentation; Survey data; SME consultation |
| | Watson & Sanderson (2007) | Anesthesia monitoring | X | | | | | AH, SRK taxonomy; semantic mapping | Document analysis; Consultation with SME |
| | Ashoori & Burns (2013) | Labour and Delivery Department teamwork | X | X | | | | AH; contextual activity template; DL; Decision wheel; Collaboration tables | Scenario analysis |

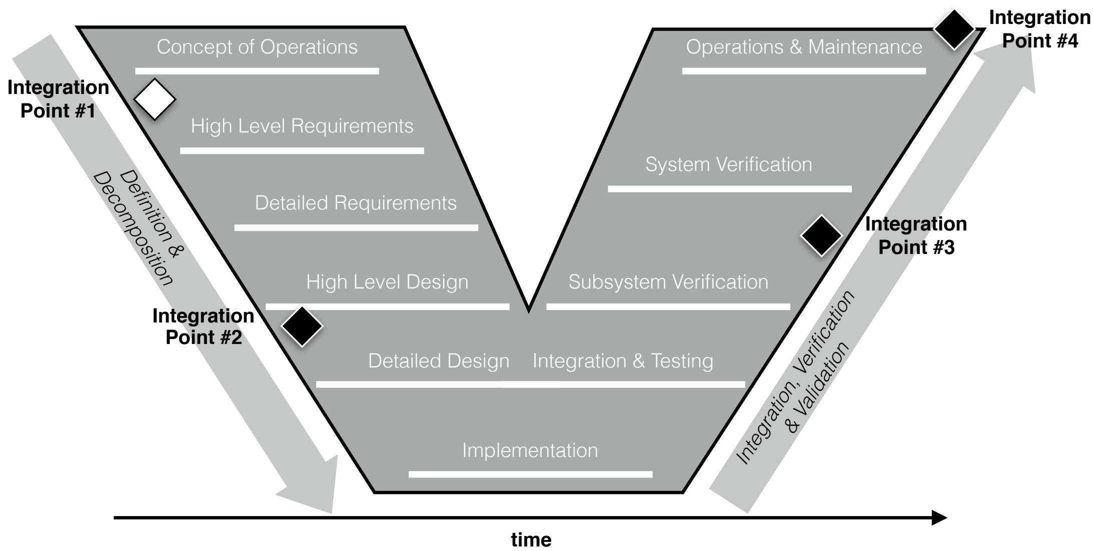



Figure 2.1: Systems engineering V-model adapted from Elm et al. (2008) overlaid with cognitive systems engineering integration points. This thesis focuses on Integration Point 1: high-level requirements.

> by the people using the system to achieve those goals (Elm et al., 2008, p. 255)."

However, few examples confirm that CSE is ideally suited to be the key breakthrough in the development of good high-level system requirements (Gualtieri et al., 2001; Potter et al., 2007; Elm et al., 2003). As a consequence, CSE insights still lack a formalized approach to incorporating these insights beyond simply identifying what data or information is needed to be included on the graphical user interface for a human operator (Elm et al., 2008). Rather than aim CWA modeling towards the generation of requirements, as expected within traditional systems engineering (Ano, 2007, 2009c, 2011).

The CSE literature includes examples of design efforts that span the possible range of the requirements definition process from omission (see Bisantz and Burns, 2009; Jenkins et al., 2009) to formal articulation of requirements in a structured format (see Elm et al., 2003; Gualtieri et al., 2001; Potter et al., 2007, 1998). Klein et al. (1993, p. 279) emphasized "rapid prototyping as a way of circumventing formal requirements derivation by starting small and implementing an evolutionary design process." While rapid prototyping is a commonly adopted and somewhat effective means to facilitate systems design in the CSE community, large-scale SE projects rarely have the resources, monetary budget, and time to implement such an approach. CSE perspectives are traditionally implemented in the latter system evaluation stages of the SE process where major restructuring of system design elements and capabilities is limited or infeasible (Elm et al., 2008).

Much of the CSE literature references requirements only tangentially as an important component of informing system design. When practitioners do emphasize requirements, they are presented in a variety of forms, such as information requirements (Burns et al., 2005; Jamieson, 2003; McGeorge et al., 2015; Roth and Mumaw, 1995), usability requirements (Pew and Mavor, 2007), cognitive support requirements (Sanderson, 2003), situation awareness requirements (Nehme et al., 2006), and display design requirements (Bisantz et al., 2003; Miller and Vicente, 2001) with limited definition, consistency, and specificity. Furthermore, while various methods have attempted to demonstrate and link CSE requirements to specific CSE model components (Cattermole et al., 2016; Cummings, 2004; Cummings et al., 2012b; Lintern, 2006; Nehme et al., 2006), the extent to which these studies emphasize the actual requirements derivation process and situate their development within traditional SE processes is limited. Although examples are deemed valuable within the CSE community for their specific domain application, if they cannot be translated to the SE community of system developers, customers and other engineers, CSE insight and influence will remain limited (McIlroy and Stanton, 2012).

At the core of traditional SE, requirements are defined by customer and user needs from relevant stakeholders at the onset of the project. Oftentimes, the cognitive requirements derived by traditional SE methods (e.g., stakeholder interviews, observations) are ill-defined, assumed, or ignored, leaving a high degree of uncertainty in the system design to successfully support cognitive functions (Militello et al., 2009). There exist deficiencies that limit the synchronization between traditional SE and CSE methods. Traditional SE methods lack the following:

- *The ability to incorporate CSE design requirements in an understandable and consistent manner:* CSE requirements are present in many forms through a variety of methods that define the work domain, the operators' roles, and the joint functioning of operator and automation, which makes it difficult for SE practitioners to embed those considerations in the larger SE process.
- *The mechanisms to trace, validate, and verify CSE requirements throughout the SE process:* A lack of CSE-inspired requirements specified early in the design process results in limited validation/verification capability of the artifact design at latter stages of the design process.
- *The considerations of user needs beyond basic information requirements, such as work context, adaption, roles, responsibilities, and function allocation:* Requirements generated by the SE process that resemble CSE requirements convey base information needs without capturing more comprehensive work context and cognitive demands.

Moreover, CSE methods lack the following:

- *Literature that both describes and demonstrates the CSE requirements derivation process, particularly for envisioned work systems:* A majority of CSE studies bypass formal requirements derivation in an effort to build prototypes to evaluate. While this is sustainable for small scoped projects, it is likely unsustainable for large-scale multiyear systems development efforts that are multidisciplinary.
- *Mechanisms or outputs from CSE methodologies that can be readily incorporated into the general SE process:* CSE methods generate a variety of products with many, sometimes complicated, models. As such, CSE insight can be lost in the translation to the larger SE community when actually interfacing with non-CSE engineers within the larger SE design team.
- *Specificity in requirements definition that aligns with SE community expectations:* The SE community expects requirements presented in the form of shall statements. However, the CSE community rarely develops shall statements that articulate the insights from CSE analyses.

One approach to integrate CSE requirements with the SE process was proposed by Elm et al. (2003) using an applied CWA framework. The applied CWA process involved first constructing a functional abstraction network (FAN) model that captured the essential work domain concepts and relationships that defined the problem space. Subsequently, a layered set of requirements were derived from FAN elements that specified cognitive work, information relationship, representation design, and presentation design requirements. The applied CWA framework was initially appealing; however, three key deficiencies of the FAN method lead us to use a modified applied CWA:

- *Limited scalability for complex work domains with numerous work domain agents and highly engineered systems:* The management of FAN elements becomes intractable as the number of interdependent linkages grows with the complex of work domains.
- *Constructing a FAN model is highly iterative, following a "bootstrapping process":* As a result, there exists a high level of overhead and limited tool support on the part of the CSE practitioner. This is compounded by the fact that there is a lack of formal literature explaining the FAN generation process.
- *Limited specific application of the FAN model to work domains outside the works of Potter and Elm* (Elm et al., 2003; Potter et al., 1998, 2007): Numerous studies exist demonstrating the application of traditional CWA methodologies; however, demonstration of FAN method is limited.

Specifically, applied CWA was adapted to leverage the more commonly utilized models from traditional CWA (Vicente, 1999). First a WDA was performed that involved the construction of an information flow model and abstraction hierarchies (AHs). Second, a ConTA was performed that resulted in a contextual activity template and decision ladders. Finally, cognitive work requirements (CWRs) and information relationship requirements (IRRs), as originally defined by Elm et al. (2003), in a traceable way by anchoring those requirements to specific stages of the decision ladder model. The CWR and IRR statements articulate the CSE perspectives critical to instill in the larger SE design process. Additionally, CWR and IRR content and format convey the characteristics expected by the SE community practitioners. Traditional requirements specification characteristics include being necessary, correct, unambiguous, feasible, achievable, prioritizable, quantifiable, measurable/verifiable, traceable, and results oriented (Turk, 2006).

### 2.1.3 Summary

The ability to make meaningful progress towards synchronizing the demands of complex sociotechnical systems with technological design starts with understanding what types of constraints and demands exist as the work is performed. The search, discovery, and formalization of problems within the situated context of those decision-making challenges requires researchers to contend with the variety of contextual features that make the problem space large, dynamic, uncertain, and high risk. Fortunately, examples exist from the CSE community such as large-scale system development efforts that describe how principled mappings between system functional decomposition can be developed in military command and control (Bisantz et al., 2003), identifying traceable links between the results of cognitive analyses and actionable design requirements in the health care informatics development (Hettinger et al., 2017; Jiancaro et al., 2013), synchronizing cockpit display logic with pilot cognitive demands (Riley, 1996; Riley et al., 1999; Riley, 2000; Riley et al., 2002), and making military battlefield constraints transparent to commanders (Bennett et al., 2008; Hall et al., 2012). The consistent thread among these examples is that to yield effective design solutions, the problems must be understood in the context of when decisions must be made and the associated work involved. When this perspective is missed, technology may not be accepted as in the case of digital flight strips being rejected by the French air traffic control community (Mackay, 1999), or worse yet when a highly automated multi-billion dollar air traffic control system is never deployed (Britcher, 1999). Given the aforementioned state of the CSE requirements derivation process, we demonstrate one potential avenue for generating CSE-inspired requirements utilizing the first two phases of CWA. However, before we begin that discussion, we review some other key aspects of the design process worth consideration.

## 2.2 Framing the Envisioned World Problem

> "How can results of studies and analyses that characterize cognitive and cooperative activities in the current field of practice inform or apply to the design process, since the introduction of new technology will transform the nature of practice, what it means to be an expert, and the paths to failure (Woods and

Dekker, 2000, p.5)?"

Contemplating the future of a work domain is unsurprisingly inherent to all design activities. However, not all design activities are shaped by the same work domain characteristics (e.g. work demands and domain constraints). While many design challenges are constrained and influenced by physics and engineering constraints, challenges in sociotechnical systems also include human physiological and cognitive constraints. Technological capabilities are becoming more substantial and designers must now be capable of selecting or identifying specific capabilities from a myriad of potential options. Furthermore, designers must systematically explore and understand these constraints to guide technological capability development efforts within a future work domain context. However, few resources currently exist to help designers over come these challenges, formally known as the *envisioned world problem*. The remainder of this section summarizes and scopes the existing literature to shape how these insights were adopted for this thesis. The intent here is to provide a common reference point from which designers can cast their own envisioned world problem.

### 2.2.1 Envisioned World Problem Definition and Perspectives

This thesis extends the foundational literature of the envisioned world problem as defined below to explore the implications they may have for designers embarking on their own envisioning process.

| **Definition: Envisioned World Problem** |
|---|
| Envisioned World Problem focuses on a central question: how can "characterizing the current domain inform or apply to the design process, given that the introduction of new technology will transform the nature of practice (Hoffman and Woods, 2000, p. 6)?" |

Figure 2.2 shows the envisioned world problem as defined by Woods and Dekker (2000), recast as a two dimensional representation. Vector $\mathbf{R}$ connects the existing work

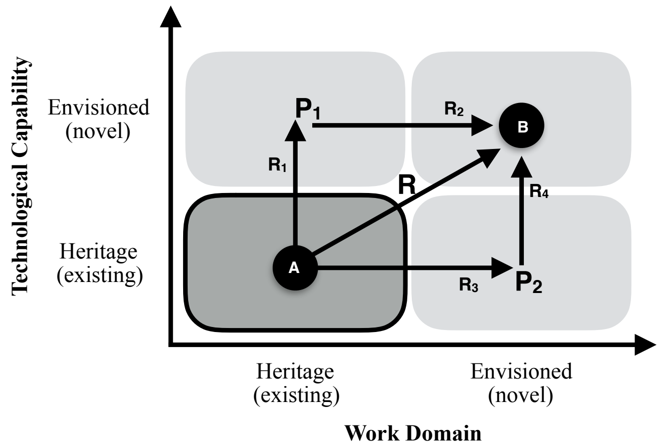



Figure 2.2: Decomposition of the envisioned world problem along the dimensions of technological capability and work domain states.

domain state (A) with an envisioned future state (B), enhanced by new technological capabilities. Vector $\mathbf{R}$ is subsequently decomposed along two dimensions: on the x-axis, the **work domain**, and on the y-axis, **technological capabilities**. Technological capabilities are defined here as a technological system intended to be designed and employed within the work domain (e.g. electronic medical records or an astronaut electronic cuff checklist). The work domain in this context refers to agents, organizational and cultural structure, technological artifacts (and their current capabilities), and work 'as-practiced' demands. From a systems engineering perspective, technological capabilities in this context are to be considered separate from the surrounding technologies already existent within the domain.

The CSE design community is prone to follow pathway $\mathbf{P_1}$ by enhancing an existing work domain (State A) with the installment of new technologies ($\mathbf{R_1}$) and then modify the work domain to use the new technology as it was intended ($\mathbf{R_2}$). Implications of these work domain modifications can include procedural, organizational or work responsibility changes. Traditionally, CSE designers contend with the challenges that exist along vector $\mathbf{R_2}$ when new technologies are already designed and implemented while opportunities to influence the design and development process along vector $\mathbf{R_1}$ are limited (Pew, 2008; Feigh et al., 2017). Technological capability enhancements are often times sourced from software developers, engineers, and stakeholders who may not fully grasp the actual work demands that exist within the domain and are often constrained by budget or procurement constraints rather than the constraints of the work to be supported.

In an idealized sense, pathway $\mathbf{P_1}$ represents a familiar approach to the envisioned world problem: a new technology is developed and installed in a work domain and a new desired state is reached by operators compensating for the deficiencies or burdens the new technologies impose on the work being performed. Contemporary exemplars of pathway $\mathbf{P_1}$ include the digital revolution of electronic medical records in the medical field (Ano, 2015b; Buntin et al., 2011), next generation automated systems in air traffic control (Sarter and Amalberti, 2000; Durso and Manning, 2008; Ano, 2015a), military command and control (Jenkins et al., 2012), and rail transport (Bearman et al., 2013). However, there exist systematic limitations to the affordances provided by pathway $\mathbf{P_1}$ and challenges practitioners must consider and overcome.

But there is another way to address the envisioned world problem. Pathway $\mathbf{P_2}$ first emphasizes the transition of the current work domain into the future work domain ($\mathbf{R_3}$) and then determines what technological capabilities are necessary ($\mathbf{R_4}$). The translation from State A to B can, and should, be performed by first emphasizing the development of the future work domain where the actors, environment, and problems are considered and translated to a future context as represented by vector $\mathbf{R_3}$. For example, if NASA aims to extend a crew of 4 or 6 people from low-Earth orbit into deep-space where they are effectively isolated from Earth-based support personnel, an understanding of the shifts in the work domain (e.g. redistribution of work functions) must be acquired before technological solutions can be made. A key aspect of vector $\mathbf{R_3}$ is that the future context is considered with heritage technological capability. In other words, the technological artifacts remain constant while the work domain characteristics are allowed to shift to meet hypothesized new work conditions.

The point here is that a choice must be made early in the envisioning process where only those technologies that are necessary by the future work domain are included. In the limiting case, existing heritage technologies provide a first step in that process. The simultaneous advancement of work domain characteristics and new technologies such as those experienced along pathway $\mathbf{P_1}$ can lead to confounding issues. The impact or perceived utility in new technological capabilities can be difficult to discern and resolve from the desired shifts in work practices. Only after the work domain along vector $\mathbf{R_3}$ is characterized within the future context (e.g. the problems and constraints are understood in a future context) with heritage technologies should the advancement in technological capabilities be hypothesized and implemented to reach the desired target (State B) as represented as vector $\mathbf{R_4}$. Some recent examples that implement this approach along pathway $\mathbf{P_2}$ include research in health care informatics (Pennathur et al., 2010; McGeorge et al., 2015; Hettinger et al., 2017). In an era where technological capability is ever increasing, practitioners must first take stock in what the actual work demands are before considering technological solutions.

Both pathways shown in Figure 2.2 aim to reach a novel, desired 'envisioned' state of operations (State B), where both work domain attributes and technological capabilities are harmoniously enhanced. Collectively, these pathways constitute a spectrum of various approaches to addressing the envisioned world problem. However, the envisioned world problem has yet to be fully explored along these pathways, and more importantly there exists a lack of guidance as to what methods and considerations could be leveraged by practitioners to define, develop, and ultimately advance their envisioned world problem along these various pathways. As suggested in the subsequent sections, practitioners should actively engage in understanding work domain demands both in the current and future context to understand where technological capabilities could be implemented to support that work. No longer can technological advancement be thought about in isolation from realistic work domain expectations (Lintern, 2012; Stary and Peschl, 1998; Carroll, 1991; Dekker et al., 2013). Furthermore, CSE designers will play an increasingly important role in the envisioning process, acting as the arbiter of design insight early in the design process that link both work domain and technological attributes to yield effective designs solutions (Feigh et al., 2017).

The extension from State A to State B exhibits pathway dependency for the practitioner to consider. Furthermore, the two pathways shown in Figure 2.2 are not equivalent in that pathway $\mathbf{P_2}$ is more conducive to yielding tenable work domain enhancement and desirable technological designs. To clarify, this thesis does not provide a 'plug-in-play' solution for practitioners. Instead, this thesis consolidates the breadth of considerations and assumptions practitioners should include as they begin to tackle their respective envisioned world problem(s). The case study presented throughout provides one example of how to approach the envisioned world problem with the expectation that the depth of discussion and characteristics presented here will guide other envisioned world problem research efforts. In effect, this thesis attempts to link the research connected with cognitive systems engineering and practical considerations of the envisioned world problem. The remainder of this section provides a summary of the existing insight pertaining to the envisioned world problem to help structure the approach taken in this thesis.

### 2.2.2 Establishing Opportunities to Acquire Domain Insight

Purposeful observation is the touchstone of all envisioning activities and is therefore central to the envisioning process. However, the scope and purpose of observation must be considered by practitioners as part of their envisioning process. Traditionally, observational settings are classically divided in two distinct stages: observations made within the actual (or natural) work setting (also known as "the wild") (see Hutchins, 1995; Patterson et al., 1999) and those made within a contrived laboratory setting (see Hutchins, 1995; Patterson et al., 1999; Egan et al., 1989; Brehmer and Dörner, 1993). The natural work setting contains the work as-practiced context necessary for domain understanding whereas the laboratory setting offers the mechanisms of control to examine targeted questions. Unfortunately, these two settings often exist in isolation and there exists a lack of research

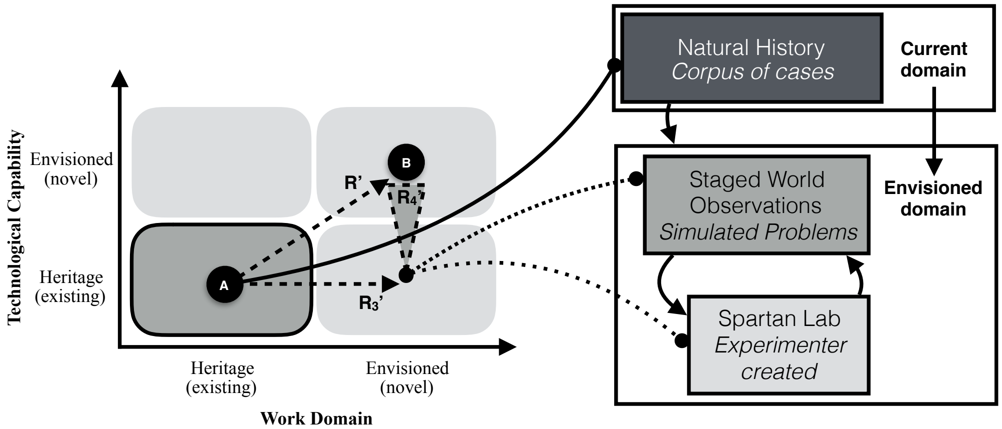



Figure 2.3: Transitioning along Pathway 2 - building insight for the future through the natural history, staged, and spartan lab world observations (observational stages adapted from (Woods, 2003)).

attempting to connect these vantage points (Brown et al., 2011; Flach et al., 2008; Lintern, 2012; Rooksby, 2013). Linking the stages of observation is integral to the envisioning process and can be accomplished using three stages of observations, as shown in Figure 2.3. While the stages of observation themselves are not new concepts, the integration of such concepts within the envisioning process itself is, see Woods (2003) for a theoretical discussion.

By structuring these stages, the issues already associated to the envisioned world problem can be addressed. Woods and Dekker (2000) highlight four perspectives to consider early in the envisioning processing as stated below:

- **Plurality**: there are multiple versions of how the proposed changes will affect the character of the field of practice in the future.
- **Underspecification**: each envisioned concept is vague on many aspects of what it would mean to function in that field of practice in the future; in other words, each is a simplification, or partial representation of what it will mean to practice when that envisioned world becomes concrete.
- **Ungrounded**: envisioned concepts can easily be disconnected or even contradict, from the research base, the actual consequences of the changes on people, technology and work
- **Overconfident**: advocates are miscalibrated and overconfident that, if the systems envisioned can be realized, the predicted consequences and only the predicted consequence will occur.

As a result, these challenges can be more directly addressed by coping with both the Natural History with the Staged and Spartan stages as described in the subsequent sections.

*Natural History*

The natural history stage of observation refers to the examination of traits exhibited by the existing (or historical) work domain. At this stage, the aim for the practitioner should be on "discovering or identifying the processes that drive performance and adaptation (Woods, 2003, p.43)" within the work domain. It is important at the onset of investigation to establish 'how' and 'for what purposes' should the domain be studied. The work domain under this context include not only psychological and technical components/limitations that already exist, but also the social and interrelationships within the domain, see (Bisantz and Burns, 2009, Ch. 8) for additional work domain considerations. Fortunately, many methods exist to examine an existing work domain that span from ethnographic investigations to applied cognitive systems engineering (CSE) methods. For an overview of the CSE field, see Rasmussen et al. (1994); Endsley et al. (2007); Hoffman and Militello (2008); Militello et al. (2009). CSE methods in particular can provide a host of appropriately defined vantage points to conduct the examination of a current/historical domain. These efforts include: contextual inquiry (Militello and Hutton, 1998; Beyer and Holtzblatt, 1998; Dekker and Nyce, 2002; Dekker et al., 2003; Feigh, 2006), cognitive task analysis (Crandall et al., 2006; Militello and Hutton, 1998), cognitive work analysis (Rasmussen et al., 1994; Vicente, 1999), and ecological interface design (Rasmussen and Vicente, 1990; Vicente and Rasmussen, 1992; McIlroy and Stanton, 2015). (See Bisantz and Roth (2008) for a comprehensive review of CSE methods and their applications.)

Additionally, some CSE literature such as those from the Contextual Design community (Beyer and Holtzblatt, 1998) does provide some useful initial insights worth considering that align well with the envisioned world problem stages of observation. First, in order to promote a successful hypothesis generation process, establishing a common language for teams of relevant design personnel to agree upon is paramount. More specifically, teams must consider the work more so than an single specific technological design solution. Second, creating a vision of what that future work will entail provides a benchmark and prototyping opportunity to promote the design synthesis process to yield effective design solutions. This thesis endorses the contextual design components of an iterative prototype development process and adopts the focus area perspectives used to describe prototype designs in the subsequent envisioned world stages of observations as described in the subsequent sections.

CSE methods collectively strive to "identify the basic requirements for how to support work that must be met if new technology will be useful to practitioners in context (Woods and Hollnagel, 2006, p.178)." For a more recent survey and burgeoning application of CSE methods applied to the health care work domain, see Hettinger et al. (2017). While these methods provide an abundance of modeling tools that aim to capture the work as-practiced, limited guidance is currently provided for progressing work domain insight into actionable envisioning efforts. More specifically, limited methodological support exists to help practitioners traverse what we identify as the 'gulf of conception'. In other words: how do we bring work-as practiced understanding into a future context? What traits of the domain are worth extending and considering in a future context? This thesis contends that design requirements is one mechanism to help facilitate this extension.

*Staged World*

The staged world attempts to situate observations within the context of envisioned operations to examine the nature of practice and to help reveal what would (could) be useful (Woods and Roth, 1988). Some research efforts that provide guidance in constructing the staged world include scenario-based design (Carroll, 2000), the future incidents technique (Smith et al., 1998), and synthetic task environment design (Flach et al., 2012). It is important within this stage of observation that the practitioner does not work in isolation. Additionally, practitioners will unlikely be directly involved in the development of these staged worlds. Therefore, the practitioner will need to put forth the effort to seek out opportunities to align their own research efforts to what may or may not be already under investigation within the community at large. When considered within the context of envisioning a future domain, the staged world provides a number of potential benefits to practitioners as summarized below:

- The staged world provides a starting point for designers to pivot their research agenda, depending on what research activities and interest already exist within the domain. In effect, designers can utilize the staged world context to scope areas of their specific envisioning process by situating their efforts within the larger community of stakeholders.
- The envisioned state of operations should be considered fluid and can accommodate a variety of perspectives. In other words, the ability to focus or extend the work performed within the future context is concrete in the sense that elements are more clearly defined, yet nothing is absolute and therefore malleable to alternative opinion and insight.
- The staged world helps calibrate the envisioning process to observe how aspects are similar or dissimilar from the current work domain. For example, scientific objectives will play a much more dominant role in defining EVA objectives in future operations. What implications will those new objectives have when imposed on an existing domain that has not dealt with scientific priorities in the past, aside from the Apollo program?
- Finally, the staged world enables practitioners to explore the variability that arises from situated operations (Turvey et al., 1978; Vicente, 2000). This opportunity not only allows subjects to become familiar with the envisioned context, but also enables the practitioners to become familiar with the implications of new/future demands. Asking and answering questions such as: Is this realistic work practice? And how might current-day standards be imposed in the future?

In summary, the staged world provides an opportunity for practitioners to gain operational experience within the future context, without contending with the volume of details necessary to describe the work domain context. This observational opportunity allows contrasts to be made between the existing domain and what the future might entail and helps identify areas for more targeted research objectives to be examined in a more controlled setting, known as the spartan laboratory.

*Spartan Laboratory*

The spartan laboratory encapsulates the more traditional experimental environments that abound within the academic literature. Commonly known as micro worlds, spartan labs provide researchers a platform with extensive control to explore theoretical model development and technology evaluation. Historically, spartan labs have suffered from a lack of work context by operating under a simplified environment which makes results difficult to generalize to the natural world; see Brehmer and Dörner (1993); Brehmer and Elg (2005); Gonzalez et al. (2005); Omodei and Wearing (1995) for examples. However, if one views the laboratory setting as being developed as part of the envisioning process, where the relevant constraints and problems found in the natural world are extended to staged and spartan settings, then a strategically scoped and relevant environment can be generated. The spartan laboratory under this context still utilizes artifacts as a tool of discovery, but within a contextually relevant setting that enables a more detailed data collection and synthesis effort. In a spartan lab setting, the opportunity to explore more targeted evaluations of new technological capabilities can be made, without sacrificing the important contextual demands of the work domain. Furthermore, the construction of the spartan laboratory itself is an excellent exercise in defining with the unavoidable assumptions (e.g. specific work practices, goals, constraints) that face the envisioned domain.

### 2.2.3 Summary

The perspectives of the envisioned world problem have been largely ignored in by both the traditional systems engineering and cognitive systems engineering communities. However, these challenges are important to recognize and address at the onset of the design process so that design choices and the resulting implications can be quantified. The stages of observation provide one useful, structured approach to viewing the challenges of designing for the future. As a result, this thesis incorporates the stages of observations with the CWA frame with the aim to build a DSS for future EVA operations and shows the value of each step and how they manifest in a serious, safety critical, realistic account of a hypothesized future.

## 2.3 Design Bases for DSS Development

Born out of the management and information sciences disciplines in the 1960's, decision support systems (DSS) have become ubiquitous computational technology with the purpose of improving system performance (Keen, 1980). While decision support systems have an extensive history of practice, there are important ramifications to consider before designing and implementing a DSS, regardless of how beneficial a DSS might appear to be. The following section discusses both the benefits and limitations of decision support systems and the potential avenues that exist to use CSE theory and modern-day web-based technologies for rapid DSS prototyping and development.

### 2.3.1 DSS Benefits and Limitations

In general, a DSS is built to process large amounts of data and display that information in a meaningful manner for the user or organization to comprehend. Subsequently, the operator or organization can then use that information to make necessary and desired decisions. For a complete review of DSS history and development, see Burstein and Holsapple (2008b,a). Common types of support provided by a DSS (as described by Marakas (2003, p. 50)) are shown below:

- Explores multiple perspectives of a decision context
- Generates multiple and higher quality alternatives for consideration
- Explore and test multiple problem-solving strategies
- Facilitates brainstorming and other creative problem-solving techniques
- Explores multiple analysis scenarios for a given decision context
- Provides guidance and reduction of debilitating biases and inappropriate heuristics
- Increases decision maker's ability to tackle complex problems

- Improves response time of decision maker
- Discourages premature decision making and alternative selection
- Provides control over multiple and disparate sources of data

Furthermore, these systems are commonly classified as one or more of various types as described below by Arnott and Pervan (2008). Personal Decision Support Systems (PDSS), Data Warehousing (DW) and Enterprise Reporting and Analysis Systems comprise the bulk of DSSs that have been built to-date.

- **Personal Decision Support Systems (PDSS)**: usually small-scale systems that are developed for one manager, or a small number of independent managers, to support a decision task.
- **Group Support Systems (GSS)**: the use of a combination of communication and DSS technologies to facilitate the effective working of groups.
- **Negotiation Support Systems (NSS)**: DSS where the primary focus of the group work is negotiation between opposing parties.
- **Intelligent Decision Support Systems (IDSS)**: the application of artificial intelligence techniques to decision support.
- **Knowledge Management-Based DSS (KMDSS)**: systems that support decision making by aiding knowledge storage, retrieval, transfer and application by supporting individual and organizational memory and inter-group knowledge access.
- **Data Warehousing (DW)**: systems that provide the large-scale data infrastructure for decision support.
- **Enterprise Reporting and Analysis Systems**: enterprise focused DSS including executive information systems (EIS), business intelligence (BI), and more recently, corporate performance management systems (CPM). BI tools access and analyze data warehouse information using predefined reporting software, query tools, and analysis tools.

As computational resources have improved, so has the ability for a DSS to utilize advanced computational techniques to better predict and even suggest decisions for users. Modern DSSs also have the potential capacity to help users “cope with a changing decision environment, problems, and user characteristics” (Cegarra and van Wezel, 2012, p. 302). These capabilities generate additional DSS benefits as shown below (described by Marakas (2003, p. 5)):

- Extend the decision maker's ability to process information and knowledge
- Extend the decision maker's ability to tackle large-scale, time-consuming, complex problems
- Shorten the time associated with making a decision
- Improve the reliability of a decision process or outcome
- Encourage exploration and discovery on the part of the decision maker
- Reveal new approaches to thinking about a problem space or decision context
- Increases decision maker's ability to tackle complex problems
- Improves response time of decision maker
- Generate new evidence in support of a decision or confirmation of existing assumptions
- Create a strategic or competitive advantage over competing organizations

Clearly, the capabilities a DSS could provide to a given work domain are desirable. However, in-spite of tremendous advancement in computer technology in recent decades, these systems do still have limitations which are important to consider. A list of notable DSS limitations is shown below as discussed by Marakas (2003, p. 5). However, as discussed in the remainder of this section, cloud computing has changed the landscape in recent years enough that the premise of some of these limitations is debatable, particularly for web-based DSS technologies.

- DSSs cannot yet be designed to contain distinctly human decision-making talents such as creativity, imagination, or intuition
- The power of a DSS is limited by the computer system upon which it is running, its design, and the knowledge it possesses at the time of its use
- Language and command interfaces are not yet sophisticated enough to allow for natural language processing of user directives and inquiries
- DSSs are normally designed to be narrow in scope of application, thus inhibiting their generalizability to multiple decision-making contexts

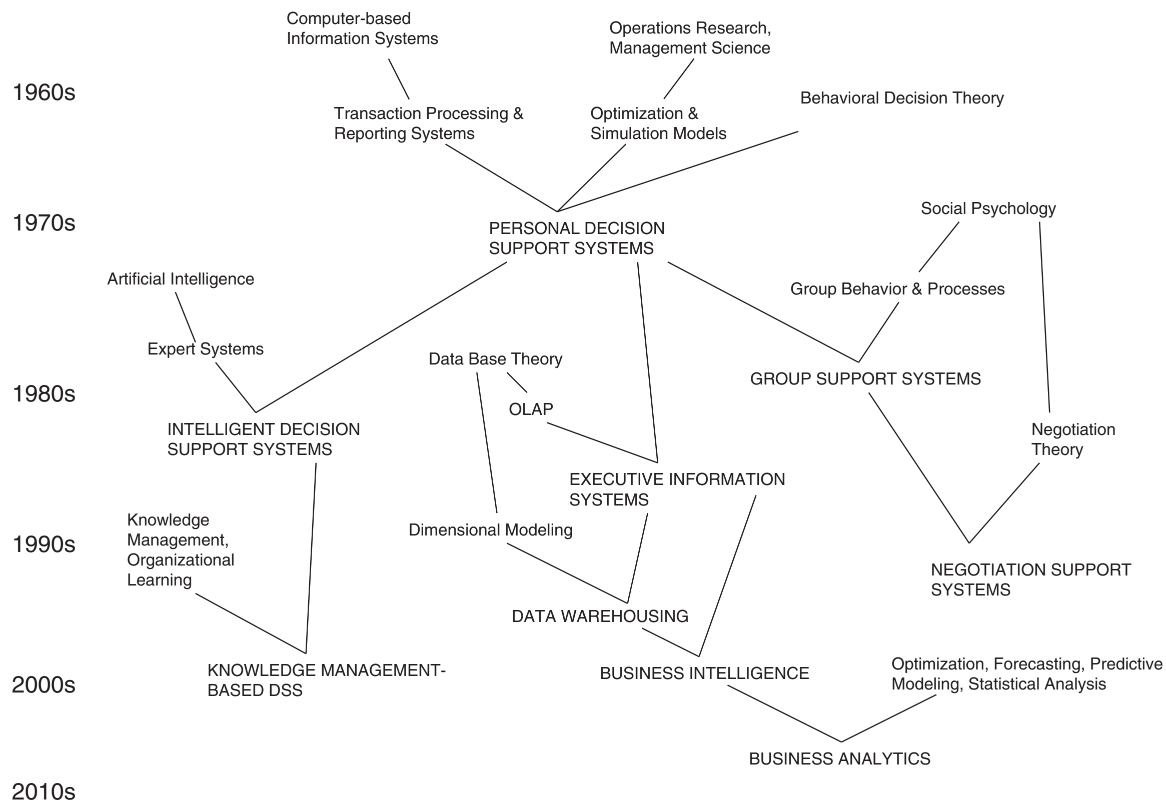



Figure 2.4: Evolution of the DSS field of research (Arnott and Pervan, 2014, p. 270).

### 2.3.2 A Brief Review of DSS Purpose

Decision support systems are rooted in the information systems discipline with the aim to improve managerial decision making. Figure 2.4 shows a summary of the focus of DSS development has evolved over the past five decades. For a summative review of the applications of decision support systems from 1971-2010, see Eom and Lee (1990a,b); Eom et al. (1998); Eom and Kim (2006); Arnott and Pervan (2014).

Consider for a moment the general heritage of DSS development as described above. Its entire purpose has centered around propelling businesses towards a competitive advantage in a capitalistic market place. An emergent focus in recent years in DSS development has been on business intelligence and analytics (Arnott and Pervan, 2014). The term business analytics refers to decision making based on the use of statistical and quantitative analyses with explanatory and predictive models. It is only recently (within the last ten years) that DSS researchers have begun tackling the challenges associated with using ‘big data’ in useful ways to make decisions. However, the verdict is still out on whether these systems have demonstrated necessity and success, see Arnott and Pervan (2014) for a review. Now consider for a moment the work domains described in Section 2.1, where support systems are utilized to promote sociotechnical system performance. While the underlying DSS concepts are similar, their applications are not. Furthermore, CSE examples often emphasize interface design as opposed to exploring the underlying software structure.

Figure 2.4 shows that DSS development has limited direct application to the complex sociotechnical systems.[1] In fact, the DSS literature has been criticized for the lack of synchronicity between academic literature and contemporary professional practice (Arnott and Pervan, 2005). In cases where DSS research does consider academic theories such as decision making theory, the emphasis is typically placed on classical decision making theory such as the works of Simon (1960) or Tversky and Kahneman (1981). As a result, there is limited demonstrations from the DSS literature considering the elements central to CSE methods and perspectives. Instead, the DSS development community draws almost entirely separate standards and methods towards DSS design science research, (see Hevner et al., 2004; Kuechler and Vaishnavi, 2012). Design guidelines such as those shown in Table 2.4 are typically leveraged for custom-built DSS applications and ‘technology-driven’ solutions. Conversely, DSS development from CSE community such as those found in nuclear power plant control centers (Guerlain and Bullemer, 1996; Vicente et al., 1995; Itoh et al., 1995), military command and control centers (Lintern, 2006; Cummings, 2004), and air traffic control centers (Feigh, 2008) have limited association to the body of DSS literature from the design sciences discipline.

Furthermore, prior studies that examined what makes a DSS successful indicate a multitude of factors are at play. For a full review of these factors, refer to Burstein and Holsapple (2008b, Ch. 34). The two key factors summarized below align well with the opportunities

[1] This is important to realize given the current call within the human spaceflight to community to extensively leverage ‘big data’ systems to support future operations.

Table 2.4: Design-Science Research Guidelines as described by Hevner et al. (2004, p. 83).

| Guideline | Description |
|---|---|
| Guideline 1<br>Design as an Artifact | Design-science research must produce a viable artifact in the form of a construct, a model, a method, or an instantiation. |
| Guideline 2<br>Problem Relevance | The objective of design-science research is to develop technology-based solutions to important and relevant business problems. |
| Guideline 3<br>Design Evaluation | The utility, quality, and efficacy of a design artifact must be rigorously demonstrated via well-executed evaluation methods. |
| Guideline 4<br>Research Contributions | Effective design-science research must provide clear and verifiable contributions in the areas of the design artifact, design foundations, and/or design methodologies. |
| Guideline 5<br>Research Rigor | Design-science research relies upon the application of rigorous methods in both the construction and evaluation of the design artifact. |
| Guideline 6<br>Design as a Search Process | The search for an effective artifact requires utilizing available means to reach desired ends while satisfying laws in the problem environment. |
| Guideline 7<br>Communication of Research | Design-science research must be presented effectively both to technology-oriented as well as management-oriented audiences. |

that are afforded from the CSE literature and the envisioned world problem.

- **Well-defined information and systems requirements**: Despite the difficulty of defining executives' requirements, the project should have an accepted definition of what is required from the system.
- **Evolutionary development**: A successful DSS should be developed iteratively with strong user involvement, evolving towards an effective application set.

There are extensive opportunities to align these two fields of research. Interestingly, many of the guidelines described in Table 2.4 share many of the sentiments that are discussed in the fields of CSE as well as the envisioned world problem. CSE has proven success in deriving the necessary work domain understanding to define what support will be needed. The envisioned world problem more appropriately scopes the challenges and opportunities to acquire insight into deriving meaningful system design purpose. Finally, the DSS research community has numerous examples of the practical implications and considerations to making and implementing DSS technology. The remainder of this section highlights the opportunities for web-based technologies to rapidly prototype DSS systems.

*Opportunities for Modern-day web-based technologies*

The DSS literature leverages technologies that typically date from the early 2000's or older, see Bhargava et al. (2007) or Burstein and Holsapple (2008b, Ch. 34) for a review. As a result, the challenges associated with web-based technologies are dated (Bhargava et al., 2007). We now live in *Internet of Things* and cloud computing that networks across devices and platforms with the ability to exchange data. The affordances provided by the internet are quickly out-pacing the legacy desktop systems the DSS literature emphasizes. The Internet's growth in users, devices and overall impact over recent decades has led to an ecosystem of powerful, open-source, easy-to-use tools for developing applications (Yaqoob et al., 2017). Web technologies lend themselves well to rapid prototyping, with cheap, well-tested and well-documented deployment and inherent cross-platform installation. In fact, web technologies have started to encroach on traditional desktop software; it is common nowadays to build desktop applications using web technologies. The rise of cloud computing has also made it affordable to deploy a web platform without excessive overhead. Furthermore, the extensive open source ecosystem now available enables development at essentially no cost.

A DSS is classically decomposed into five elements as shown in Figure 2.5 (Marakas, 2003). To handle the raw information, the data management system must store and manage the information for retrieval. The information must then be prepared by the model management system to simplify the analytic studies necessary for the work domain (Power and Sharda, 2007). The knowledge management system then does the processing to generate solutions to the associated identified problems (Özbayrak and Bell, 2003). Finally, the DSS must then display this information to the operator as well as accept any inputs the operator may have to the DSS. The user element pertains to the operator who must interact with the DSS and ultimately make the necessary decisions to complete their respective activities.

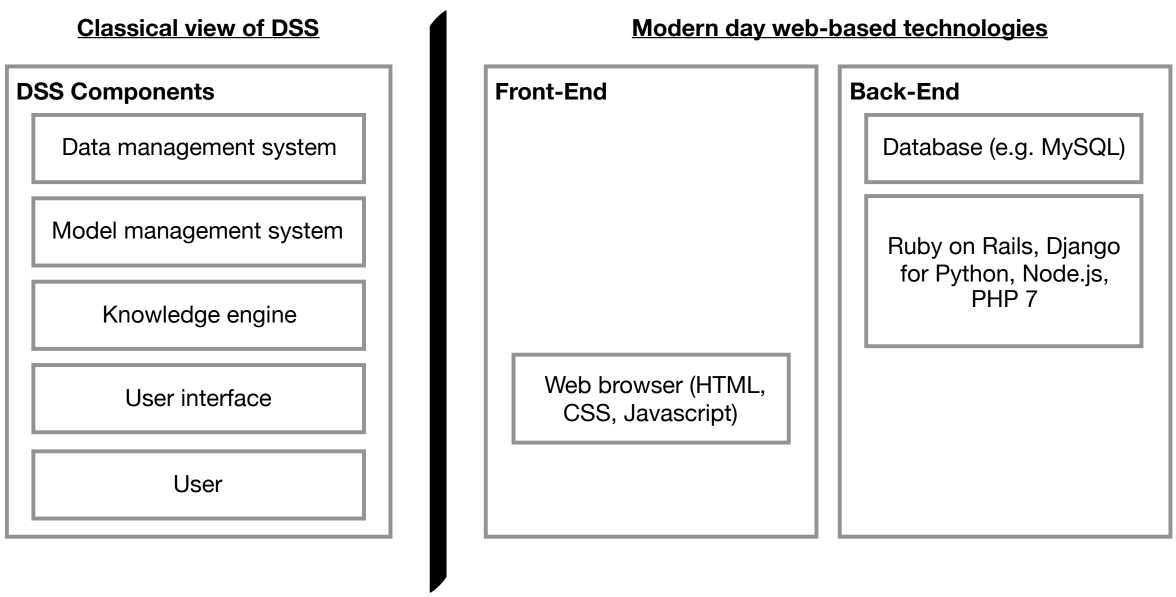



Figure 2.5: DSS components (Left) and existing web-based technologies (Right) now available to support system development.

Modern websites can be decomposed into two main domains: the front-end and the back-end.[2] For back-end development, there now exists numerous, open-source databases (e.g. MySQL, PostgreSQL) that can handle vast amount of data of all types efficiently and reliably. Furthermore, object relational mapping (ORM) capabilities exist in many back end contexts, such as Ruby on Rails or Node.js, to query and manipulate information held in databases. As for the front-end development, web browsers leverage the combined utility of HTML, CSS, and Javascript to generate sophisticated user interfaces to view, interact with, and manipulate data.

### 2.3.3 Summary

The fields of CSE and DSS development offer complementary expertise to contribute towards the development of complex sociotechnical systems. CSE methods offer a means to integrate the necessary domain constraints demands of sociotechnical systems to be instilled within DSS designs. Additionally, web-based technologies provide a new avenue for DSS development that has previously not been recognized by the community of practice. The availability of open-source libraries and frameworks can shorten the development process time so that elements such as the knowledge management system and interface design can take center stage in the development process. The remaining component of this effort is to situate these development efforts within a sociotechnical system such as the EVA work domain, discussed in the subsequent section.

## 2.4 Introduction to Human Extravehicular Activity

As indicated in the previous sections, there is a need to understand the demands and work context of both the existing and future EVA operations to help develop technologies to support those operations. Therefore, the simultaneous development of the work domain and the support tools within that domain must be considered together to reveal useful system design insight for envisioned systems (Deans and Hoffman, 2010b,a; Hoffman et al., 2010).

[2] https://github.com/kamranahmedse/developer-roadmap

In doing so, support system design must include "the users' points of view, how they are viewing the work, how they are interpreting the task, how they are adopting or rejecting strategies, and how they are modifying or abandoning standard procedures (Crandall et al., 2006, p. 164)."

The following section summarizes the research efforts performed to-date that address both the present-day EVA work domain and also potential future operations. NASA has over 50 years of experience conducting EVA in low-Earth orbit (LEO) and on the lunar surface which provides a valuable starting point to guide EVA DSS development.

### 2.4.1 EVA from a Historical Perspective

The term, Extravehicular Activity (EVA), also known as a spacewalk, is defined below:

> **Definition: Extravehicular Activity**
> Extravehicular Activity is "any space operation or activity performed outside the protective environment of a spacecraft therefore requiring supplemental or independent life support equipment for the astronaut (McBarron II, 1994, p. 5)."

EVA is divided into three distinct categories as defined by Covington (1974):

- **Scheduled EVA:** defined as a planned event that been practiced on the ground by all relevant personnel long before being performed in space.
- **Unscheduled EVA:** defined as an unplanned event that is essential to ensure mission success.
- **Contingency EVA:** defined as an unplanned event that is critical to the safety of the crew.

The majority of EVAs performed to-date have been Scheduled EVA, each of which incorporated years of planning and development in order to perform. Various historical perspectives exist that discuss *what* EVA tasks and objectives have been executed, see Wilde et al. (2002); McBarron II (1994); Ross (1994) for reviews. Attempts have also been made to capture 'lessons learned' while performing EVA (see Brown, 1973a,b; Tremblay, 1994; Barer, 1991; Fullerton et al., 1994a,b; Wilde et al., 2002; Ross, 1994). The vast majority of these reviews however are engineering and hardware focused. This is not surprising considering the technology required to keep a human alive in the vacuum of space is highly complex. There are strictly regulated requirements for consumables such as breathable air and carbon dioxide levels, in addition to thermal and operational safety constraints to ensure the safety of the astronaut while performing EVA. Tremblay (1994) and Portree and Treviño (1997) summarize critical EVA capability and safety considerations shown in Table 2.5.

Table 2.5: EVA Capabilities and Safety Considerations (Tremblay, 1994; Portree and Treviño, 1997).

| EVA Capabilities | EVA Safety Considerations |
|---|---|
| Technology Demonstrations | Contamination or Corrosion |
| Spacecraft and Payload Inspection | Impact or Collision & Radiation |
| Spacecraft Servicing | Electrical Discharge or Shock |
| Payload Repair | Loss of Habitable Environment |
| Payload Deployment | Temperature Extremes |
| Scientific Experimentation & Testing | Environmental |
| Structure Construction & Assembly | Pathological or Physiological |
| Device Installation | Fire or Explosion |

To enable the capabilities and account for safety considerations shown in Table 2.5, NASA implements a regimented training schedule to prepare astronauts for their EVA tasks. During the Apollo era, preparation for an EVA was typified by 13 hours of simulated EVA for each hour of actual EVA. However, as the mission objectives became more aggressive during the Skylab and Shuttle/ISS programs, the rate at which EVAs were being performed exceeded the time available to maintain such an intensive training schedule. In the late 1990's, Wilde et al. (2002) estimated the ratio of training to actual EVA hours to be 3:1 for Shuttle/ISS EVAs and speculated that the ratio would continue to reduce as NASA pushed towards even more ambitious EVA capabilities. This trend has slowed since the termination of the Shuttle program, however future missions will once again stress the *a priori* training schedule due to the extend mission durations that will be spent between training for an EVA and performing the EVA.

Within the existing body of EVA literature, the formal study of *how* EVA operations is conducted is limited, particularly when compared to other operationally similar work domains such as air traffic control and military command control. The EVA work domain, as it exists today under real-time communications, exhibits a dependent relationship between extravehicular (EV) crew and the mission control center (MCC). Ground support personnel actively influence nearly all aspects of astronaut activities, including EVA, using a network of communication voice loops that connect teams of specialized flight controllers, see Patterson et al. (1999) for a review of MCC organizational structure. In effect, crew are inherently reliant upon the active participation of ground support personnel to provide updates, alterations, and recommendations to maintain timeline progress to achieve the EVA objectives (Bell et al., 2006). As a result, the EVA work domain as a whole has yet to be fully defined as a sociotechnical system.

### 2.4.2 Past & Current Research Activities

The majority of research within the EVA community to-date has been dedicated to the technological and operational challenges associated with the tools and hardware related to the suited astronaut. These challenges include (a) reducing the time and resources required to prepare an astronaut for EVA through skill-based training, as opposed to task-specific training (Thuot and Harbaugh, 1995; Bell and Coan, 2012; Ney et al., 2006), and (b) enhancing overall capabilities of the spacesuit (Hodgson et al., 2003; Jaramillo et al., 2008; Abercromby et al., 2010; Reid et al., 2014; Reid and McFarland, 2015). Additional efforts have assessed astronaut task execution efficiency (Looper and Ney, 2005, 2006; Marquez, 2010). Various EVA timelines were decomposed into content categories to quantitatively describe the time spent in each category to identify aspects of an EVA that warrant efficiency improvements - that is, how can we reduce crew time spent during, or increase crew efficiency on, particularly long or challenging EVA tasks? A host of physiological studies have also been dedicated to better supporting crew health during EVA operations, see

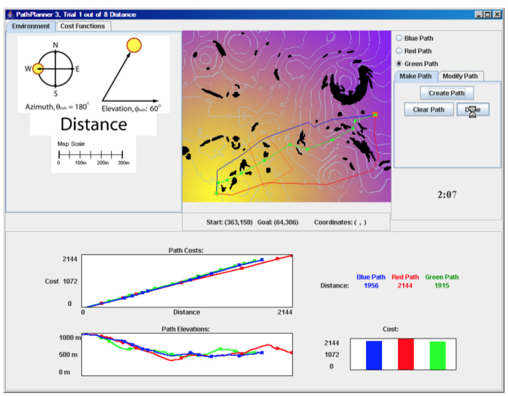
Cowell et al. (2002) for a review. However, these 'astronaut-centric' studies while valuable, provide only one component of the larger volume of perspectives and considerations necessary to successfully execute EVA.

### 2.4.3 Envisioning Future EVA Operations

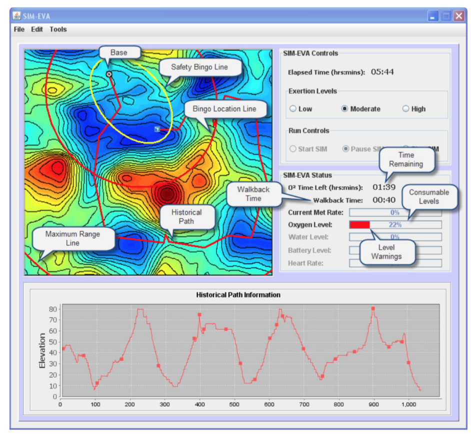
To transition from present-day operations understanding to deep-space operations, NASA has conducted numerous analog test campaigns to situate crew in relevant, flight-like conditions, such as micro-gravity at Near-Earth Objects, moons of Mars and Mars surface. Much of this work has investigated architectural components and support capability requirements of proposed concept of operations that span the entire flight control team which consist of EV crew (e.g. the EV crew performing the spacewalk tasks), IV crew (e.g. co-located astronauts located within a spacecraft or vehicle), and MCC support personnel (e.g. specialized flight control operators situated on Earth). Table 2.6 shows an abbreviated summary of recent NASA studies performed (and currently in progress). A variety of time-delayed conditions have been explored that represent various operational work environments and prototype EVA tools/hardware, see Table 2.6. Additionally, a range of gravity environments that simulate NEO, moons of Mars, and Mars surface operations have been tested. Cumulatively, these studies establish a hypothesis of future EVA concept of operations, task procedures, tools, and hardware which have yielded a variety of operational insight. For instance, sending audio messages across time-delay from the Earth-based controllers to EV crew has limited utility due to the work dissociation that occurs when operating in asynchronous communication environments (Rader et al., 2013). In other words, audio messages can be disruptive and challenging to incorporate because they no longer align with the local state of affairs. Additionally, architectural components such as additional crew members and mobile vehicles such as the Space Exploration Vehicle (SEV) have been shown to enhance EVA operations. Finally, these studies have identified favorable concepts of operations for future crew that utilize an intravehicular (IV) operator as a critical arbiter of communication, command, and control between EV crew and MCC (Abercromby et al., 2013a).

Traverse path planning and optimization efforts have also been conducted to optimize surface EVA operations (Johnson et al., 2009, 2010; Marquez and Cummings, 2008; Cummings et al., 2012a) Constraint-based optimization methods were applied to account for terrain elevation, lighting, and energy expenditure to examine how various level of path planning optimization influenced a users path planning process, as shown in Figure 2.6a. Subsequent work then combined the traverse path optimization methodology with EVA consumable constraints to derive real-time walk-back limits based on consumable usage (Mackin et al., 2010). Figure 2.6b shows examples of the resulting boundaries of feasibly accessible terrain based on crew life support system limiting consumables. In addition to these efforts, the Life support, Exploration Guidance Algorithm and Consumable Interrogator (LEGACI) program was prototyped to synthesize non-invasive EVA sensor data such as heart rate, suit inlet/outlet liquid cooling garment temperature and flowrate, suit outlet gas and dewpoint temperature, carbon dioxide levels, suit $O_2$ pressure and other variables to produce metabolic rate estimates that could be interacted with via crew voice commands. The LEGACI development effort hypothesized that by increasing the capabilities of the spacesuit, EV crew could manage more of their EVA suit informatics in relation to their task duties (Kuznetz et al., 2008). A commonality amongst these envisioning efforts is the limited examination of what the current EVA work domain demands of its operators. Instead, hypothesized capabilities are situated within hypothesized scenarios and situations with limited unified directly or association to the existing EVA work domain.

As of July 27th, 2016, NASA had performed 391 EVAs, 28% of which experienced significant incidents such as crew injury, early termination, system and operational issues (Packham and Stockton, 2016). At a rate of nearly 1 in 3 EVAs encountering a significant incident, how might future crew cope with both nominal and off-nominal operations without the immediate assistance of Earth-based personnel? EVA operations is dynamic,




(a) EVA traverse path planning optimization (Marquez and Cummings, 2008).




(b) EVA walk-back constraints incorporating path planning optimization with life support constraints (Mackin et al., 2010).

Figure 2.6: Previous EVA support system research studies.

Table 2.6: Previous NASA analog field tests of extravehicular activity concept of operations.

| Reference | Analog Program | Year | Time Delay[a] | EVA Gravity Environment |
|---|---|---|---|---|
| Abercromby et al. (2010, 2012) | Desert RATS[b] | 2009 | None | Terrestrial at Mars |
| Bleacher et al. (2013); Gruener et al. (2013); Young et al. (2011); Eppler et al. (2012) | Desert RATS | 2010 | No delay | Terrestrial at Mars |
| Abercromby et al. (2013a) | Desert RATS | 2011 | 50 sec | Micro-gravity at NEOs |
| Abercromby et al. (2013b) | RATS | 2012 | 50 sec | Micro-gravity at NEOs |
| Chappell et al. (2011) | NEEMO 14 | 2010 | None | Partial gravity at Moon |
| Chappell et al. (2013a) | NEEMO 15 | 2011 | None, 50 sec | Micro-gravity at NEOs |
| Chappell et al. (2013b) | NEEMO 16[c] | 2012 | 50 sec | Micro-gravity at NEOs |
| Chappell et al. (2016) | NEEMO 18<br>NEEMO 19<br>NEEMO 20 | 2014<br>2014<br>2015 | 5 & 10 min<br>5 & 10 min<br>None, 5 & 10 min | Micro, Milli, and Partial gravity at NEOs and Mars |
| Lim et al. (2010, 2011); Miller et al. (2016b) | PLRP[d] | 2005-15 | None, 50 sec, 5 min | Micro-gravity at NEOs |
| Beaton et al. (2017); Deans et al. (2017) | BASALT-1 | 2016 | 5 & 15 min | Terrestrial at Mars |
| Chappell et al. (2017) | NEEMO 21 | 2016 | 15 min | Partial gravity at Mars |

[a]For review of NASA analog time-delay studies, see Radar et al., 2013Rader et al. (2013)
[b]For review of D-RATS, (Ross et al., 2013, see)
[c]For review of NEEMO, (Reagan et al., 2012, see)
[d]For review of PLRP, see (Lim et al., 2011, see)

training intensive, high-risk, and dependent on the ability to cope with the unexpected (Bell et al., 2006; Coan and Bell, 2012). The types of problems and cognitive demands that face the current EVA work domain will likely remain in future operations.

EVA missions will play a critical role in future missions. To enable EVA operations in deep-space, the incorporation of more advanced human-system technology for a sustained human presence beyond LEO has been proposed. Recently published literature outline the need for intelligent machine systems to support humans in a variety of roles, which include mobility, data acquisition, information technology, autonomous science and assembly, and decision-making (Gross et al., 2000; Mendell, 2004; Shafto et al., 2012; Major et al., 2010). Kostakos (2010) summarized recent crew evaluation studies in deep-space environments conducted in within the European Space Agency (ESA). These activities include preliminary work in evaluating cognitive and psychomotor performance, observing crew interaction, and monitoring the mental and emotional state of the crew . From a mission control standpoint, Sim et al. (2008) highlights the need for improved situation awareness to enhance flight controller performance as well as the need for on-board real-time decision making capability for the astronaut in an asynchronous communication environment . Decision supports system(s) are one possible solution to addressing these issues. However, the incorporation of additional technologies and tasks for crew members to manage must be done without creating distraction or imposing detrimental workload.

## 2.5 Shaping the Researcher's Worldview

To this point, I have examined the opportunities and deficiencies within a variety of literature domains. But before I present the specific contributions of this research, it is important to comment on my worldview as a researcher that shaped the execution of this work. Research is commonly classified as either qualitative or quantitative. However, this thesis incorporated a blend of the two into a mixed-methods research approach. Specifically, this research involved an exploratory sequential mixed methods research approach (see

Creswell (2014)) where I first performed a qualitative research phase that consisted of Cognitive Work Analysis and supporting contextual design models to help inform a quantitative second phase that consisted of prototype development and human-subject experiments.

Underpinning my mixed-methods approach is my *pragmatic worldview*. Pragmatism is a "worldview that arises out of actions, situations, and consequences rather than antecedent conditions (Creswell, 2014, p. 10)." In other words, instead of specifically focusing on research methods, I implemented a multitude of approaches to better understand the specific research problem. For a review of these methodological perspectives, see Creswell (2014). The overall intent of this research is to contribute to the underlying science needed to develop decisions support systems for the EVA work domain for future mission operations. As a consequence of my worldview, I implemented methods, techniques, and procedures that best met my needs and purposes to better understand this problem by converging on support system designs that reflected the contextually relevant features of the work domain. Rather than presupposing technological capabilities or solutions, my pragmatic point of view led me to first obtain a broad understanding of the EVA work domain that enabled me to quantitatively investigate more targeted aspects of the research problem.

## 2.6 Contributions

Design requirements are the medium through which a systems design is realized and vetted in practice. Therefore, this thesis aims to demonstrate, as part of the first stage of the SE process, the CSE requirements can be derived by applying the CWA methodology and then posited in a compatible SE requirements format. Specifically, this work incorporates the first two phases of CWA - work domain analysis (WDA) and control task analysis (ConTA) - to define and ground the research effort and to derive a set of decision support system (DSS) requirements for future human spaceflight extravehicular activity (EVA) operations, respectively.

Currently, NASA aims to send humans beyond low Earth orbit, and the EVA work domain serves as an evolutionary work domain for the application of the proposed CSE requirements derivation process.The goal of this work is to provide an example of how a CSE practitioner can generate requirements from analyzing a complex work domain as it exists today to inform and shape how it will exist in the future. An inherent hypothesis in this research is that the requirements definition process needs to be separated from the actual representative prototype design. Requirements do not provide design solutions (Zave and Jackson, 1997). By explicitly establishing a set of CSE-inspired requirements, CSE insight can be more readily carried throughout the SE process in the form of requirements. The exact physical representation of the resultant support system should be thought of as a hypothesis derived from the CSE requirements. Only once requirements are established can the CSE requirements be referenced and tested to verify and validate the representative design.

The development of future EVA operations will require a foundation in understanding what capabilities are and are not necessary. The aforementioned capabilities represent a spectrum of hypothesized support capabilities future crew could utilize during EVA operations. Yet, there still exists a need to synchronize the necessary support capabilities with the envisioned work of future EVA crew. Studying the EVA work domain, given the mission critical capability it provides, is an appropriate domain for the application of DSS development. Furthermore, the active NASA analog research programs provides an opportunity to incorporate both the existing and the envisioned stages of observation. The searching for necessary resources is paramount to gathering empirical evidence for guiding what kind of support system will be developed (Taylor et al., 2013). However, providing more capabilities does not always lead to improved performance (Lafond et al., 2012). Additionally, more technological support does not always actually yield more support (Lerch and Harter, 2001). Therefore, as reiterated throughout this study, researchers need to be dedicated to understanding the underlying cognitive demands inherent to the work being supported and facilitate the transition from the present-day work domain to an envisioned one. Rather than strictly emphasizing technology capabilities, work context and the operator work functions need to be part of the discussion (Meshkati, 1991; Dekker and Woods, 1999).

As motivated by these prior discussions, the contributions for this thesis fall into two broad categories and are complimentary:

1. Contributions specific to support future EVA operations in deep-space environments
2. Contributions to Cognitive Work Analysis for system design for the broader class of sociotechnical system design

With respect to contribution (1), this thesis seeks to generate design solutions to address specific technical challenges specific to the EVA work domain as defined below:

1.1 *Identify the constraints of the EVA work domain and associated decision support system design requirements for future EVA operations*

The EVA work domain is defined and characterized. Specifically, a series of cognitive work analysis models are constructed to identify and define the key operators, communication pathways, constraints and work demands that shape EVA operations within the existing work domain. This examination of the current domain provides a basis from which design requirements can be generated to being the prototype development process for future operations.

1.2 *Detail the design characteristics of both the future domain and prototype DSS designs*

The derived design requirements are combined with in-situ field study campaigns to specify key components of future EVA operations and how DSS prototypes can be situated to promote effective EVA execution.

1.3 *Provide an evaluation of a prototype decision support system for future EVA operations*

This investigation further demonstrates the implementation and evaluation of DSS prototypes within future EVA operations. In doing so, the prototype designs were assessed relative to their specified design requirements and each other to assess overall design effectiveness.

With respect to contribution (2), this thesis seeks to demonstrate a novel application of the Cognitive Work Analysis framework for system design as specified below:

2.1 *Integrate CWA model components with the specification of design requirements for prototype development*

The requirements definition process is enhanced and extended within the first two phases of the Cognitive Work Analysis framework by more explicitly linking subject-matter experts states of knowledge to unique system design requirements. The requirements are known as Cognitive Work and Information Relationship requirements (CWR and IRR). These extensions address a key gap in the current literature: CWA constraints and demands can fail to be adequately incorporated into the broader systems engineering design process.

2.2 *Demonstrate the prototype development process, situated within the construction of a future work domain*

The derivation of design requirements are carried through an initial prototype design development and evaluation process to demonstrate overall utility.

# CHAPTER 3

# COGNITIVE WORK ANALYSIS OF THE EVA WORK DOMAIN

As discussed in Chapter 2, CWA has been applied to a multitude of work domains with various degrees of success. However useful, CSE practitioners provide only one recent perspective on systems design; and one which is not well known outside of the cognitive engineering and human factors domains. Therefore, the CSE methods such as CWA must prove their worth by providing tangible outcomes. CWA insights are often captured within models that are difficult for the larger design community to easily synthesize and translate them into practice. To address these concerns, the following chapter details the CWA modeling and development efforts in a way that is relatable to the larger systems design community and specifically the EVA community. I demonstrate how to utilize the first two phases of CWA as a means to derive requirements that guide subsequent DSS prototype development efforts. The contribution of this work is two fold: 1) illustrate the utility of CWA for requirements derivation and 2) derive requirements for EVA support. The value of the CWA is to provide a common ground from which all members of the design community can orient themselves to the underlying constraints that exist in the work domain of interest.

Nevertheless, the identification of constraints and demands that exists within a particular work domain, which are the standard result of CWA, are not sufficient to generate useful DSS design (McIlroy & Stanton, 2015). Formal design requirements are the foundation of interface design and assessment in traditional systems engineering processes; however, few studies utilize CSE methods, such as CWA, for the purpose of requirements specification. The few that incorporate requirements have varied levels of applicability to audiences within the broader design community (Sanderson et al., 1999; Burns et al., 2005; Ernst et al., 2006; Cattermole et al., 2016). As a result, the insights captured by CSE practitioners are either represented in prototyped designs or abstract models, both of which force the broader design community to interpret and translate conclusions for themselves.

This chapter supplements previous CWA applications by depicting how the CWA framework can not only extract meaningful insight from a complex work domain but also relate those CSE perspectives to the system design process by more explicitly articulating high-level design requirements (See Figure 3.1). Rather than attempting to directly derive the interface representation from the CWA models, this work provides a case-based example of formalizing cognitive support and purpose via cognitive work requirements (CWRs) and and associated information relationship requirements (IRRs). These design requirements are derived directly from the insights obtained via the decision ladder model development performed during the second phase of CWA, known as the control task analysis (ConTA). As a result, a traceable requirements set is created from CWA that can be integrated more readily within the broader design efforts within the domain of application.

Figure 3.1 shows the steps performed to examine the EVA work domain. The first two phases of CWA were performed. The first phase involved the implementation the Work Domain Analysis (WDA) where an information flow model was initially built to define the domain structure and identify key operators within it. Then a set of abstraction hierarchies were built to describe the goals and constraints that exist within the domain (see Section 3.2.2)). Once a broad understanding of the domain was obtained from the WDA, the second phase of analysis involved the control task analysis (ConTA) where an activity template and decision ladders were constructed to provide a more targeted examination of specific work function demands. Finally, a set of DSS requirements was generated from the decision ladders that took the form of cognitive work and information relationship requirements (see Section 3.3.2).

As Figure 3.1 shows, the CWA was applied to the current work domain, but the overall intent of this investigation is to construct meaningful systems to support operations in an envisioned context. That is, we are not designing systems for the current domain, but rather learning what demands are likely to exist in the future context to shape how those

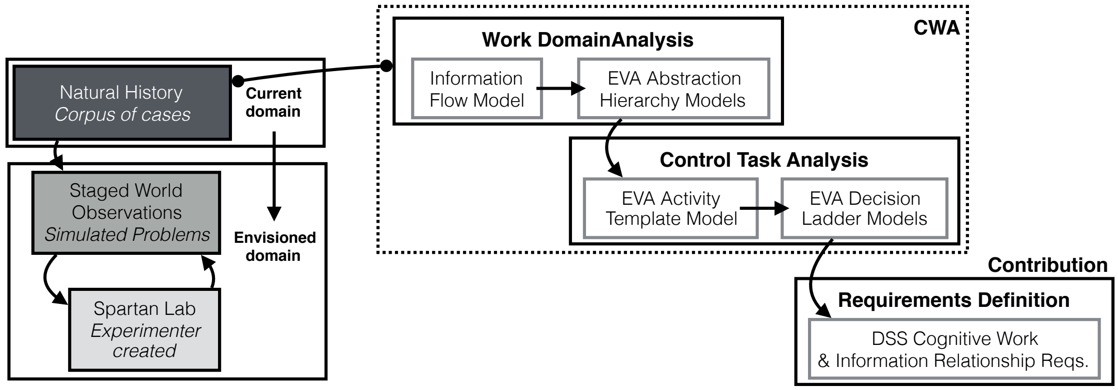



Figure 3.1: Cognitive Work Analysis phases of research as applied to the EVA work domain.

demands might be supported in that future context. No single CWA model provides a clear representation of specific design solutions, but rather the models collectively provide a road-map of design rationale to help focus the design without getting distracted by current day ‘workarounds’ and support system deficiencies based on current day tools. The goal of this chapter is to establish at a set of design requirements to be used as a basis for designing and evaluating prototypes as discussed in Chapters 4 and 5.

### 3.1 NASA EVA Operations Experiences

This study employed a number of directed efforts to become embedded within the EVA work domain. These efforts involved working on-site at the NASA Johnson Space Center (JSC) in Houston, Texas which is the NASA human spaceflight center where all NASA EVA operations occur. The insights and conclusions of these cumulative on-site experiences were embedded within the CWA models developed in the subsequent sections. In total, this study involved approximately 40 weeks spread over 4 years on-site at JSC interacting with, interviewing, and observing EVA subject-matter-experts (under NASA Grant NNX13AL32H). Figure 3.1 provides an overall summary of my CWA model development efforts alongside various research milestones. Each of the following subsections detail the particular CWA model development and validation/verification steps taken to ensure model validity.

Table 3.1: Research activities mapped to primary model development efforts. Each respective model development and validation steps are detailed in their respective subsections.

| Legend: * at NASA center; ^ at NASA analog; ~ Initial dev.; ○ Prelim.; ✔ validation | | | WDA | | ConTA/Requirements Definition | | Requirements Definition | Prototype Development |
|---|---|---|---|---|---|---|---|---|
| | | | Information Flow Model | Abstraction Hierarchies | Activity Template Model | Decision Ladder Models | | |
| 2014 | Summer | May | ~ | | | | | |
| | | Jun* | ~ | | | | | |
| | | Jul* | ~ | | | | | |
| | | Aug*/^ | ~ | | | | | |
| | Fall | Sept | ○ | | | | | |
| | | Oct | ○ | | | | | |
| | | Nov | ○ | ~ | | | | |
| | | Dec | ○ | ~ | | | | |
| 2015 | Spring | Jan | ✔ | ○ | | | | |
| | | Feb* | ✔ | ○ | | | | |
| | | Mar | ✔ | ○ | | | | |
| | | Apr* | | ✔ | ~ | ~ | ~ | |
| | Summer | May* | | ✔ | ~ | ~ | ~ | |
| | | Jun*/^ | | ✔ | ○ | ○ | ○ | |
| | | Jul*/^ | | | ○ | ○ | ○ | |
| | | Aug*/^ | | | ○ | ○ | ○ | |
| | Fall | Sept | | | ○ | ○ | ○ | |
| | | Oct | | | ✔ | ○ | ○ | |
| | | Nov* | | | ✔ | ○ | ○ | |
| | | Dec | | | ✔ | ○ | ○ | |
| 2016 | Spring | Jan | | | | ○ | ○ | DSS Prototype Development & Human-in-the-loop experimenation |
| | | Feb | | | | ○ | ○ | |
| | | Mar | | | | ○ | ○ | |
| | | Apr | | | | ○ | ○ | |
| | Summer | May* | | | | ○ | ○ | |
| | | Jun*/^ | | | | ○ | ○ | |
| | | Jul*/^ | | | | ○ | ○ | |
| | | Aug*/^ | | | | ○ | ○ | |
| | Fall | Sept | | | | ○ | ○ | |
| | | Oct | | | | ○ | ○ | |
| | | Nov^ | | | | ○ | ○ | |
| | | Dec | | | | ○ | ○ | |
| 2017 | Spring | Jan* | | | | ✔ | ✔ | |
| | | Feb | | | | ✔ | ✔ | |
| | | Mar | | | | ✔ | ✔ | |
| | | Apr | | | | ✔ | ✔ | |
| | Summer | May | | | | ✔ | ✔ | |
| | | Jun*/^ | | | | | | |
| | | Jul | | | | | | |
| | | Aug | | | | | | |

Within the EVA community, I interacted primarily with the EVA Management Office, Mission Operations Directorate EVA Flight Controllers, and the EVA Life Sciences directorate who are members within the EVA community at JSC. Additional personnel/divisions included the Space Human Factors as well as the Astromaterials Research and Exploration

Science (ARES). The main source of subject matter experts (SMEs) resided within the EVA flight controller community since they are the personnel who are trained and certified to support EVA operations.

In total, this study enrolled 9 subject-matter experts (SMEs) from the EVA operations community at different stages of this investigation through a 'snow-ball' sampling technique. My network within the EVA community expanded from each interview by asking for recommendations on additional SMEs who might be willing and available to participate in my study. Cumulatively, the SMEs participated in 30+ hours of one-on-one interview sessions divided among 22 individual interview sessions from Summer 2014 to Spring 2017, along with numerous informal ad hoc interactions during my time at JSC. In addition to SME involvement, numerous observation sessions were completed: 3 ISS EVAs (21+ hours) and 1 EVA simulation training session (7+ hours) were observed from within the Mission Control Center (MCC). Additionally, 4+ Apollo/Shuttle/ISS EVA archived audio/video footage both from previous missions as well as training simulations were also observed. Finally, Apollo lunar surface EVA operations documents were examined and analyzed as part of a historical examination of EVA operations.

Complementary to SME interaction and field observations, I performed an extensive EVA work domain literature review that resulted in the review of 480+ extravehicular activity related publications, manuals, reports that included both internal NASA documentation as well as publicly available sources. Access to internal NASA sources in particular were vital to familiarize with the domain so that my interviews could be more directed and effective at eliciting information. It was necessary to become familiar with the jargon, people, equipment, domain expectations, etc. so that conversations were focused on the information about EVA that was not already stated in written EVA documentation.

All of these efforts collectively served to make my CWA modeling efforts as comprehensive and focused as possible. The following sections decompose the steps performed and discuss the resulting insights gleaned from each individual CWA modeling effort. The process of knowledge elicitation and development of domain understanding was constantly evolving. At the beginning of this process, preconceived notions of what EVA work domain support capabilities would be needed or desired were not presupposed. Additionally, my involvement and familiarity with the domain itself was limited at the onset of analysis. Thus the contents of this chapter is generalizable to other CSE practitioners new to the work domain they are working to support and develop.

## 3.2 EVA Work Domain Analysis

### 3.2.1 WDA Methods and Models

Work Domain Analysis comes in many forms and has been applied to a multitude of domain settings, see Naikar (2013) for a review. WDA traditionally results in the creation of an abstraction hierarchy (AH) to describe a particular domain at various levels of abstraction that span from the overall objectives to the physical hardware that exists within it. From AH models, design insights have typically been translated directly to prototype designs that make the linkages between work domain elements transparent to users during operations as well as fully supporting all of the functions specified. This application of WDA is known as ecological design (see McIlroy and Stanton (2015) for a review) and is not how I applied WDA to the EVA work domain. Instead, I applied the WDA in a more traditional sense. That is, I performed the WDA not to yield user interface design solutions directly, but rather to deeply comprehend the nature of the complex work that exists within the EVA work domain. Only by first comprehending the intrinsic demands and constraints, can adequate requirements be articulated to enable users to meet their work demands of the envisioned work domain.

I constructed two models to start this knowledge elicitation process. The information flow model, also known simply as flow model, was leveraged from the contextual design community to generate a "bird's eye" view of the EVA work domain (Beyer and Holtzblatt, 1998, p.95). While not commonly a part of the CWA framework, information flow models have demonstrated value early in the work domain analysis phase to obtain an orientation within the work domain of study (Cummings and Guerlain, 2003; Cummings, 2004). The information flow model conveys the organizational structure of the work domain by examining the people, their responsibilities, and the paths of communication that exist between them, independent of time or a particular mission. In addition, the model describes the work artifacts found within the domain along with potential breakdowns that could exist within the communication paths. An excerpt from an information flow of airline operations is shown in Figure 3.2. For additional examples of the application of the information flow model, see Beyer and Holtzblatt (1998); Cummings (2004); Feigh and Pritchett (2010). Finally, my application of the information model differs from its traditional application within CWA framework usually at later stages analysis (e.g. Strategies Analysis). Instead of defining and exploring specific strategies for performing particular tasks, the information flow model was used as a mechanism to first understand what responsibilities and communication pathways exist in the present-day work domain.

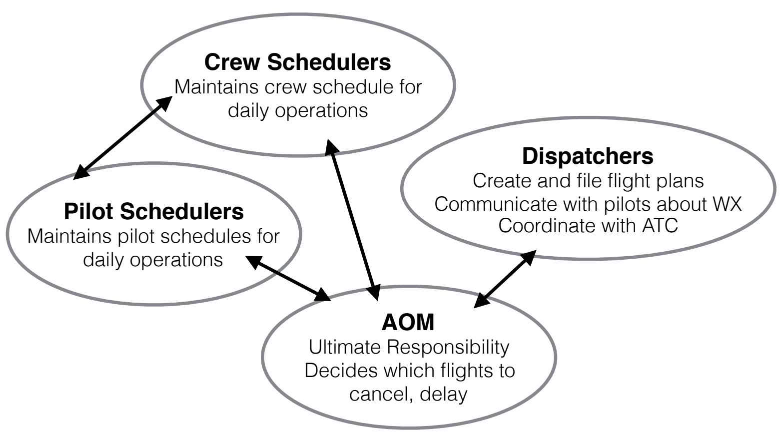



Figure 3.2: Abbreviated Information flow model example of airline operations (Feigh and Pritchett, 2010).

Complementary to the information flow model, abstraction hierarchy (AH) models were built to provide a graphical depiction of the structure and functioning of the work domain. This study utilized the traditional five abstraction levels described below (Rasmussen, 1985; Burns et al., 2005):

- **Functional Purposes:** describes the reason(s) or purpose(s) of the system.
- **Abstract Functions:** describes the principles or priorities of the work domain that are preserved, conserved, maximized or minimized, such as the conservation of mass and energy.
- **Generalized Functions:** describes the functions that must be present for the functional purpose of the work domain to be fulfilled.
- **Physical Functions:** describes the capabilities of the physical elements within the work domain.
- **Physical Forms:** describes the properties such as physical form and configuration of the physical elements within the work domain.

To help facilitate the AH model development efforts, the guiding prompts and keywords provided by Naikar et al. (2005, p. 33) were particularly useful to maintain and coordinate the variety of observational, semi-structured interviews, and literature review data sources. (See Appendix A.1 for the AH model development protocols).

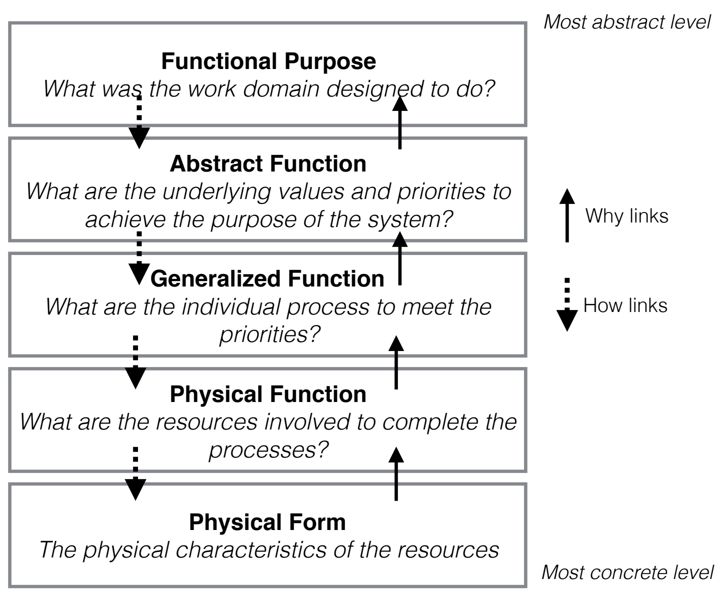



Figure 3.3: Abstraction hierarchy model decomposition (Naikar, 2013)

I performed an iterative information-gathering and model (AH and information flow model) development process that lasted approximately one year. The data sources used for the WDA were varied and extensive (see Figure 3.2). These data sources (literature review, observations, and interviews) were chosen according to their accessibility and intimate association to the EVA work domain (Naikar et al., 2005; Vicente, 1999).

Table 3.2: WDA data collection and model development/validation process.

| *Timeline* | Observation | Interview | Model | Validation |
|---|---|---|---|---|
| *5/14-7/14* | 4 EVAs (2 nominal and 2 off-nominal) audio/video archived footage) (~26 hours) | | | |
| 7/9/14 | | ~ | | |
| 7/23/14 | | ~ | | |
| 10/3/14 | | ~ | | |
| 10/7/14 | | ~ | | |
| 1/1/15 | | | IF and preliminary AH models developed | IEEE 2015 publication of IF model, HFES 2015 publication of preliminary AH models |
| 2/25/15 | ISS Increment 42 EVA 30 (8 hr) | | | |
| 3/1/15 | ISS Increment 42 EVA 31 (7 hr) | | | |
| 4/24/15 | Mock EVA Simulation (7 hr) | | | |
| 5/1/15 | | ◯ | | |
| 5/6/15 | | ◯ | | |
| 5/19/15 | | ✔ | | ✓ |
| 5/21/15 | | ✔ | | ✓ |
| 6/15/15 | | ✔ | IF and AH models completed | ✓ |
| **Totals** | 26 hours of archived + 22 hours of in-person ISS EVA operations | 4 hours of exploratory interviews + 5 hours of model review and follow-up | Preliminary & Final Models developed | Models and publication manuscripts reviewed by SMEs |

| Legend |
|---|
| ~ Semi-structured interview with SME (1 hr) |
| ◯ EVA Sim Follow-up with SME (1 hr) |
| ✔ WDA Model Review with SME (1 hr) |

Given the highly procedural and detailed nature of the EVA operations, I leveraged existing console manuals that delineated the specific expectations of the work to be performed by all members of the EVA community. I recognize that detailed operational documentation may not be available for many other work domains, in which case more direct observations and interviews may be required to articulate the same level of work detail. First, an open-coding scheme was applied to the various data sources to identify the primary operators and construct a layout of operators within the EVA work domain, characterized by EVA operator work responsibilities, geospatial locations, and associated work artifacts. This type of scheme was selected because of the exploratory nature of this phase of the research. It provided an opportunistic and exploratory lens through which to examine the data and develop the WDA models without relying on predetermined perspectives or assumptions. The data was studied by generating labels that summarized the content into distinct categories for model construction (Miles and Huberman, 1994). The labels were then refined and manifested themselves as the specific information flow model components. As a result, a final information flow model of the EVA work domain was generated. Near the completion of the flow model, two AHs were developed using another open-coding scheme to identify the specific functions present within the work domain: one that depicted the EVA environment and one that incorporated the work of EVA operators and their engineered systems. Again, the open-coding scheme was utilized on the various data sources to identify labels that were used to summarize the content and construct the AH models. Refinement to the AH models were made based on in-person observations of EVA operations. The guiding questions used to facilitate this model development process is shown in Appendix A.1. Finally, three certified EVA flight controllers reviewed the AHs to assess the content and validity of each AH element. The final forms of each WDA model were approved by at least one certified EVA flight controller.

### 3.2.2 WDA Modeling Results

*EVA Information Flow Model*

The EVA work domain is shaped by two main considerations: (a) the geospatial distribution of a variety of EVA operators and systems and (b) the potential habitable environments of the flight crew. Figure 3.4 shows the primary operators involved during present-day EVA operations. Astronauts, known as the extravehicular (EV) crew, are located outside their spacecraft and are inextricably constrained by the confines of their spacesuit. EV crew are also typically accompanied by assets such as robotic aids. The hull of the spacecraft encapsulates the operators within the spacecraft, known as the intravehicular (IV) crew, who exist locally with the EV crew. The IV crew are typically unsuited astronauts who rely on the internal environment of the spacecraft for life support needs and protection from the external environment. The external environment surrounding the in-space crew imposes severe physical constraints that result in sophisticated engineered systems necessary for EV and IV crew to simply survive in EVA environments, let alone perform their expected tasks. Finally, the EVA work domain includes the mission control center (MCC), located on Earth. A subset of personnel within mission control known as EVA flight controllers are dedicated to EVA support.

EVA ground personnel are divided into three primary console positions: systems, task, and airlock systems within the multipurpose support room. They directly support the EVA front room controller. The arrows shown in Figure 3.4 identify the primary communication pathways utilized during EVA for EVA-specific support personnel. EVA multipurpose support room (MPSR) consoles speak directly with the EVA front room controller, who then communicates with co-located personnel in the front room, such as the flight director and ground IV. Controllers located within the same room also speak directly with one another to exchange information. Finally, messages are condensed and transferred to the crew via the capsule communicator (CAPCOM) and ground intravehicular operator, also known as the "Ground IV". The vehicle and assets, such as communication and power systems, required to support EVA operators are managed by the IV operator and teams of other personnel also located in MCC. The remainder of this discussion is dedicated EVA pertinent flight controllers only.

At the top of the MCC hierarchy is the Flight Director whose ultimate role is to act as the governing authority to maintain crew safety and ensure overall mission success. The Flight Director has final authority over all decisions that are made during the entire mission, not just during the EVA. The Flight Director must manage the decisions governing the entire human/spacecraft system. CAPCOM is the only person, along with the Ground IV, in the MCC allowed to verbally communicate with the crew. They serve as the focal point of the information generated within MCC and the information coming from the crew.

The IV crew is the EVA field marshal, dictating the pace and productivity of the EVA by

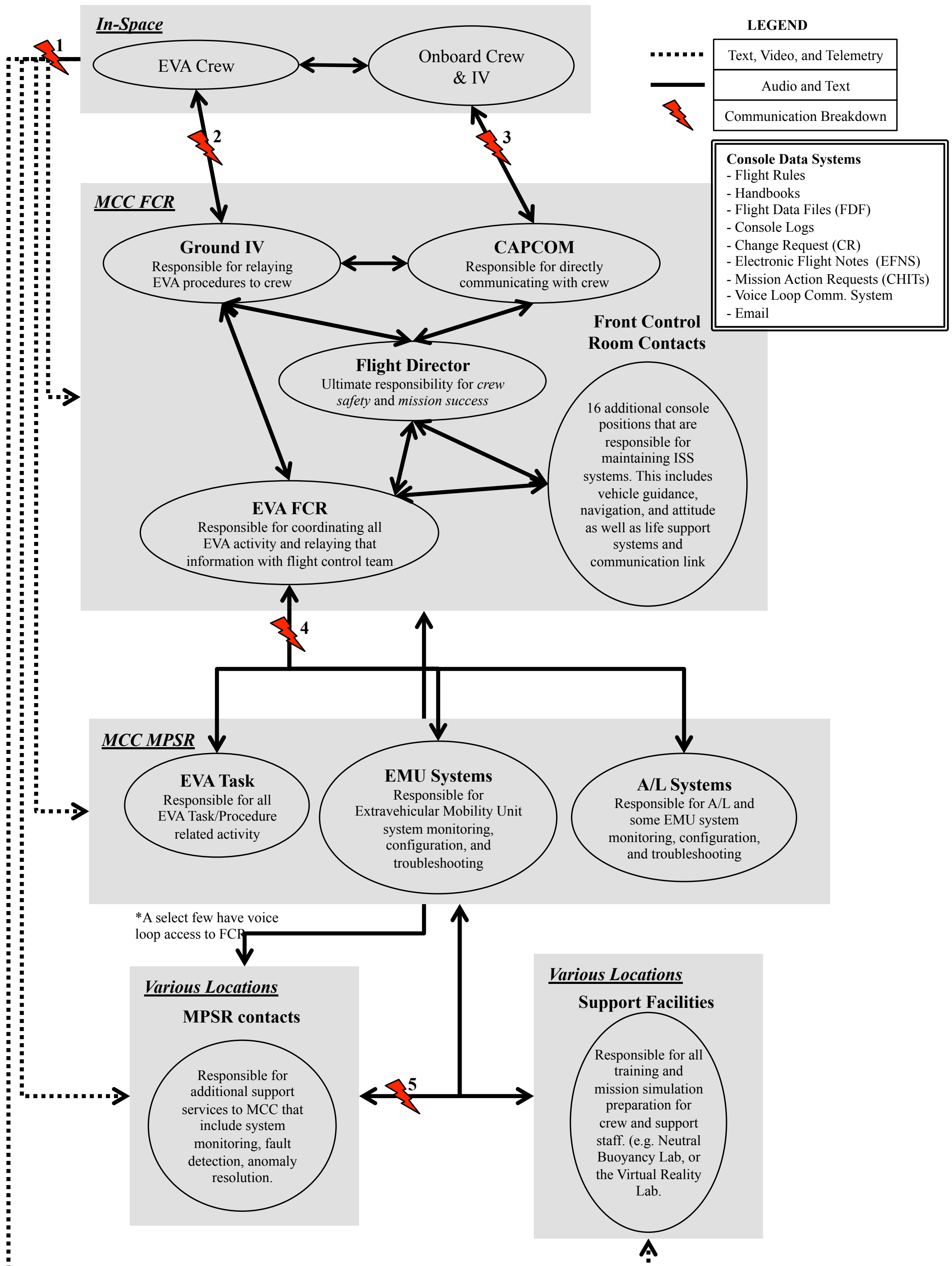



Figure 3.4: ISS EVA Operations Information Flow Model.

verbal communication with the EV crew and MCC. ISS operations incorporate a Ground IV whereas past programs such as the shuttle program placed the IV crew onboard the spacecraft. This adjust is in largely due to the lengthy mission timelines crew perform during ISS operations ( 6 month rotations). The EVA timeline the crew were trained with oftentimes changes and the Ground IV plays an important role in capturing and conveying those changes during EVA operations. In either case, they closely monitor EVA progress with the intent of minimizing error in task performance. They control the EVA checklists and procedures and manage the integration of all communication flow between the EVA crew and MCC personnel. They are also heavily involved in the pre-EVA procedures as well as the post- EVA tasks, ensuring all procedures and checklists are properly completed.

The EVA FCR is the lead EVA team member in MCC who is responsible for coordinating all EVA activity in the MCC, which includes maintaining accurate console logs, tracking the execution progress and developments, reporting anomalies, assessing the impact of those anomalies on EVA operations, and recommending appropriate action to the Flight Director. This operator leads the EVA team on all aspects of the EVA from pre to post EVA tasks and interfaces with pertinent MCC FCR personnel as needed. They are also responsible for the development of the EVA checklists and procedures.

To support the tasks and responsibilities of the EVA FCR, there exist three positions within the MPSR known as EVA Task, EMU Systems, and Airlock Systems. These operators are the primary handlers of the raw data sent from the crew and spacecraft to MCC. It is common to have one or more support personnel such as those doing on the job training sit with these MPSR operators to assist them in their duties.

The EVA Task primary role is to monitor and manage the progression of the EVA tasks within the timeline. This MCC position is the EVA expert for all task procedures and responds to any task anomalies or problems that may arise during the EVA. EVA Task handles the execution of task 'workarounds' and coordinates procedural updates with the rest of the EVA support team. EVA Task is also tasked with the responsibility of tracking tool usage and stowage. Their primary data sources are audio and video downlink to track EVA progression.

The responsibility of the EMU system rests with the EMU Systems operator, who handles all system monitoring, configuring, and troubleshooting that may arise during the EVA. EMU Systems also provides EMU system updates such as consumable status to the rest EVA support team, and assesses the impact of the EMU on the EVA timeline and assists in monitoring crew health. EMU Systems is the primary tracker of the crews' limited consumables (e.g. $O_2$, $CO_2$, power, water etc.) and reporter of crew status to the rest of the EVA Operators. Their main data sources in addition to the audio and video downlink is the EMU suit telemetry.

During pre-EVA and post-EVA, an Airlock Systems operator manages tasks related to airlock operations. Responsibilities include aiding in some EMU system monitoring alongside the EMU Systems operator, but mainly coordinates EVA tasks that interface with airlock systems. Also, the Airlock Systems operator assesses timeline alterations with airlock considerations and provides recommendations and workarounds to the rest of the EVA support team. Airlock Systems leverages the telemetry data as well as the audio and video data to monitor and maintain understanding of the vehicle systems as it pertains to EVA interfaces.

The remainder of the EVA support staff are classified as secondary operators, which consist of a multitude of personnel, more than there is room for in this one study to discuss in detail. In summary, secondary operators provide supplementary information and support to the primary operators pertaining specifically to EVA. These operators include, but are not limited to, flight controller consoles such as the Flight Surgeon, the Environment Control and Life Support Systems (ECLSS), Operations Support Officer (OSO), Robotics Operations Systems Officer (ROBO) and Communications and Tracking Officer (CATO) in MCC FCR. The examination of all FCR console positions is outside the scope of this study but the reader is encouraged to consult Patterson et al. (1999) for further detail of

MCC operations. Each MCC FCR operator has MPSR consoles that provide additional support and analysis capability. In addition to these personnel, there exists another layer of support that includes Mission Evaluation Room (MER) operators and SAFETY. These positions provide the "nuts and bolts systems knowledge to the rest of the support team. Additional operators also include all the support facilities staff who were involved with the EVA tool development, testing, and training of the EVA crew. Examples of such facilities include the Neutral Buoyancy Lab (NBL) and Virtual Reality Lab. An overview of these facilities and more can be found in Jairala et al. (2012); Osterlund and Lawrence (2012); Abercromby et al. (2013b).

In terms of communication channels, the highest priority communication pathway is the air-to- ground transmissions, which all operators listen to at all times. But only a select few operators (the crew members, ground IV and CAPCOM) can speak on this voice loop. The information flow exhibits a top down hierarchy with information flowing down from the in-space crew to the various support teams. Each operator utilizes a multitude of data sources, but specifically uses electronic flight notes (EFNs), mission action requests (CHITs), JEDI messages, the Anomaly database, electronic crew timeline (OSTPV), and change requests (CR) data entry systems for real-time data processing and transfer. Each position is also responsible for accurately logging their activities within their electronic console logs. In addition to their electronic resources, each console position has copies of the MCC flight rules and console specific handbooks. Both these documents are an assimilation of best practices and guidance expected to be implemented during support operations. In addition to these digital systems, oftentimes operators utilize paper products such as annotated documents and print-outs of timeline and systems details.

The MPSR operators handle and analyze the raw data which consists of audio, video, text and telemetry. They then pass along their interpretations and recommendations to the MCC FCR. From the MCC FCR, the information then flows through the Flight Director. The Flight Director interacts directly with the EVA FCR for EVA related activity, and also maintains contact across all the other FCR consoles to maintain system wide understanding. The information from EVA FCR is passed to the Ground IV and/or CAPCOM depending on the relevancy of the information. Non-EVA related systems knowledge is primarily channeled via the CAPCOM and EVA relevant information is transmitted via the Ground IV. Personnel preference dictates whether the information is verbally re-communicated by the Flight Director to CAPCOM or Ground IV, or rather simply agreed upon by verbal or nonverbal communication. There also exists a communication channel between the Flight Director, Ground IV, and EVA FCR that occurs face to face and is not over the voice loops.

Another area of important communication traffic is between the EVA FCR and the EVA MPSR, who are located in separate control rooms (same building). They rely on the voice loops and console data entry systems as a means to transmit their knowledge of the EVA systems and timeline progress. The EVA FCR is concerned with integrating the various aspects of the EVA such as timeline and EMU consumables, and relies on EVA Task and EVA Systems to provide that insight, respectively. To aid in their monitoring and anomaly resolution capabilities, the EVA MPSRs rely on input from the various MPSR support operators. The Mission Evaluation Room (MER) is an important source of data for the EVA MPSR operators. The EVA MER operators in particular convey the necessary technical details of the tools and equipment needed by the MPSR and FCR personnel and provide an additional level of system monitoring, fault detection, and anomaly resolution.

Disturbances in communication among the EVA operators can occur, even under nominal operations. The air-to-ground transmission can experience loss of signal (LOS) events (indicated by lightning 1, 2, and 3) which prevent communication and data transfer. Video data is lost more frequently than audio data, which can impair MCC situation awareness. These LOS events are typically known and have a duration on the order of a few seconds to tens of minutes. During this time, the crewmembers and MCC are forced to work in an isolated fashion relying on the EVA timeline, checklist, and personal training/experience until communication can be reestablished. Finally, communication between the all operators is complicated by the desire not to interrupt each other.

There is a lot of information that must be channeled between the operators in a succinct and efficient manner as possible. Two other disturbances exist which are identified by lightning 2 and 3. They include EVA timeline alterations and spacecraft updates. EVA replanning requires the Ground IV to adequately relay that information to the crewmember for implementation. Poor communication, and lack of specific knowledge can lead to improper task execution. From a spacecraft perspective, CAPCOM must perform similar duties to ensure the spacecraft systems are updated to the necessary configurations for proper EVA execution (i.e. ensure the electrical system is turned off and on when a module is replaced by a crew member). Common practice in performing real-time EVA modifications is to send a preliminary outline of the changes to the crewmembers, to let the give feedback. However, if changes are made during the EVA phase, replanning instructions are primarily restricted to audio communication with limited time for discussion of the changes due to time constraints.

Communication disturbances are also present between the MCC operators as highlighted in lightning 4 and 5. The EVA FCR is concerned with "big picture" items such as overall timeline execution progress and EVA integration with other spacecraft subsystems where as the MPSR operators are concerned with the minutiae of EVA operations. In particular, the MPSR operators are constantly monitoring real-time flight data and comparing that information with their own expected values (trend monitoring). Data trends either follow what they expect or they deviate; but in either case, MPSR operators must inform the EVA FCR of their status. The threat of information overload and of inadequate knowledge transfer between these operators are ever present. As indicated by lightning 5, there also exists the threat of over reliance on the MPSR support teams such as MER by the MPSR and MCC. This additional layer of EVA support also introduces additional opportunities for poor communication and inadequate coordination.

Additional considerations exist that are not limited strictly to the EVA support operators. The MCC has a structured authorization process, where the Flight Director has final authority on transmissions sent to the crewmembers. Even already preapproved EVA procedures, such as those on the EVA crib sheet, must pass through the proper channel for authorization in real-time. Additionally, there are many voice loops running concurrently that must be synthesized by many operators. The risks of task saturation and information overload were repeatedly mentioned during the interviews as commonplace among most operators during real-time operations.

*EVA Work Domain Artifacts*

Alongside all MCC EVA operators is a suite of work domain artifacts that help them perform their work. Figures 3.5 and 3.6 show examples of the console systems used by the EVA front room and multipurpose support room controllers. These software tools provide detailed views of subsystems associated with the airlock and spacesuit throughout EVA operations. Depending on the console position and desired action of the operator, various other software tools may be displayed including console logs, flight notes, flight data files, and anomaly management systems. In addition, each console consists of a communication system to support direct communication with other members of the MCC team. The data shown in Figures 3.5 and 3.6 are representative of the volume of data the in-space crew are currently not expected to observe or manage during EVA execution. Instead, telemetry from spacesuits, spacecraft, and hardware are sent to MCC for processing, synthesis, and resultant direction.

In addition to digital console displays, EVA work domain artifacts include a variety of paper-based products. One key artifact is the EVA timeline (and its various forms) as shown in Figures 3.7 and 3.8. EVA is one of the most scripted, planned, and coordinated events that astronauts perform. As a result, a detailed set of procedures that can range from anywhere from 20 to 80 pages are developed throughout the planning and training process so that nearly every minute of the 7+ hours of EVA is specified. Two views of timeline

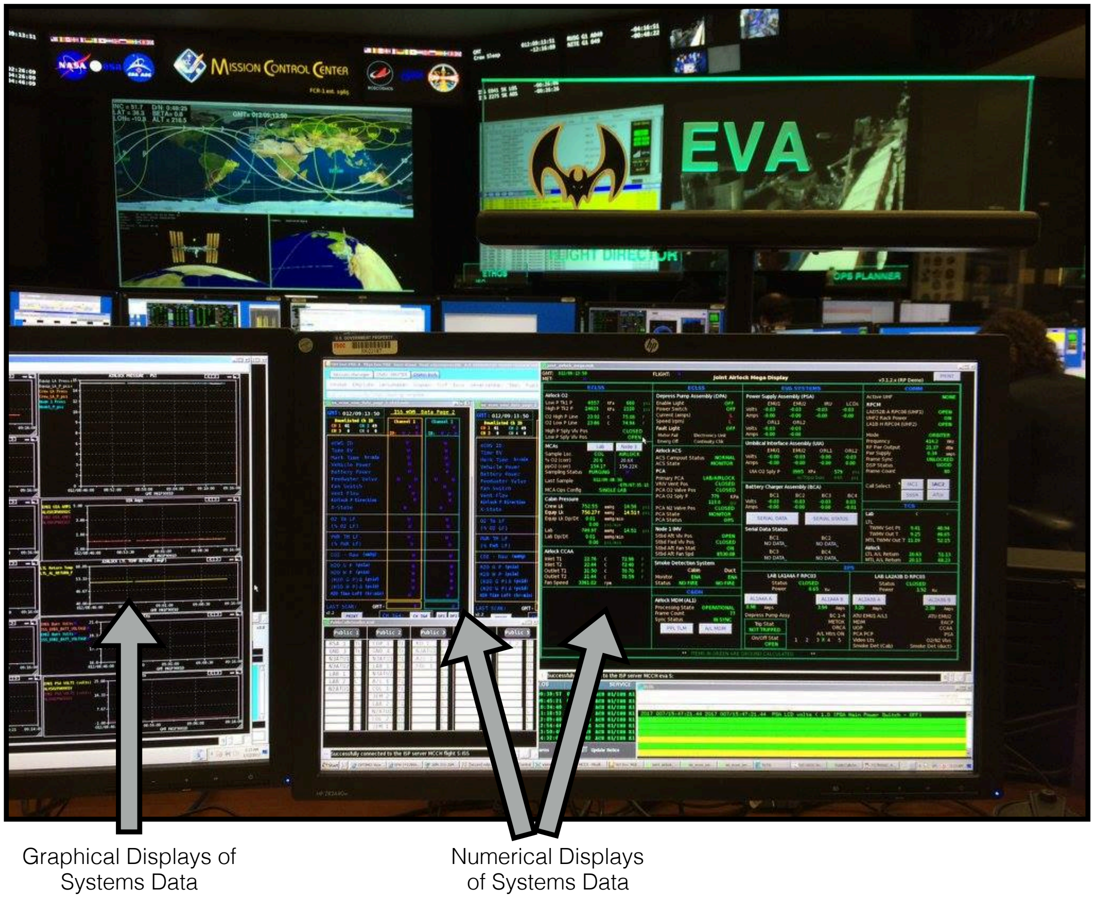



Figure 3.5: EVA front room controller console display example.

information exist: 1) a summary timeline view and a 2) a detailed procedure view. Figure 3.7 shows an annotated example of an ISS EVA summary timeline that conveys 6.5 hours of EVA activities. Each activity has detailed procedures associated with them as shown in Figure 3.8. The level of detail included in the timeline is EVA objective and activity dependent and can vary from EVA to EVA.

*EVA Information Flow Model Summary*

In summary, the information flow model shows the variety of specialized operators involved during EVA operations. Furthermore, each operator performs variety of responsibilities using specialized console systems. While the astronauts assume the greatest personal risk in conducting the spacewalk, it is up to the rest of the team to minimize that risk by ensur-

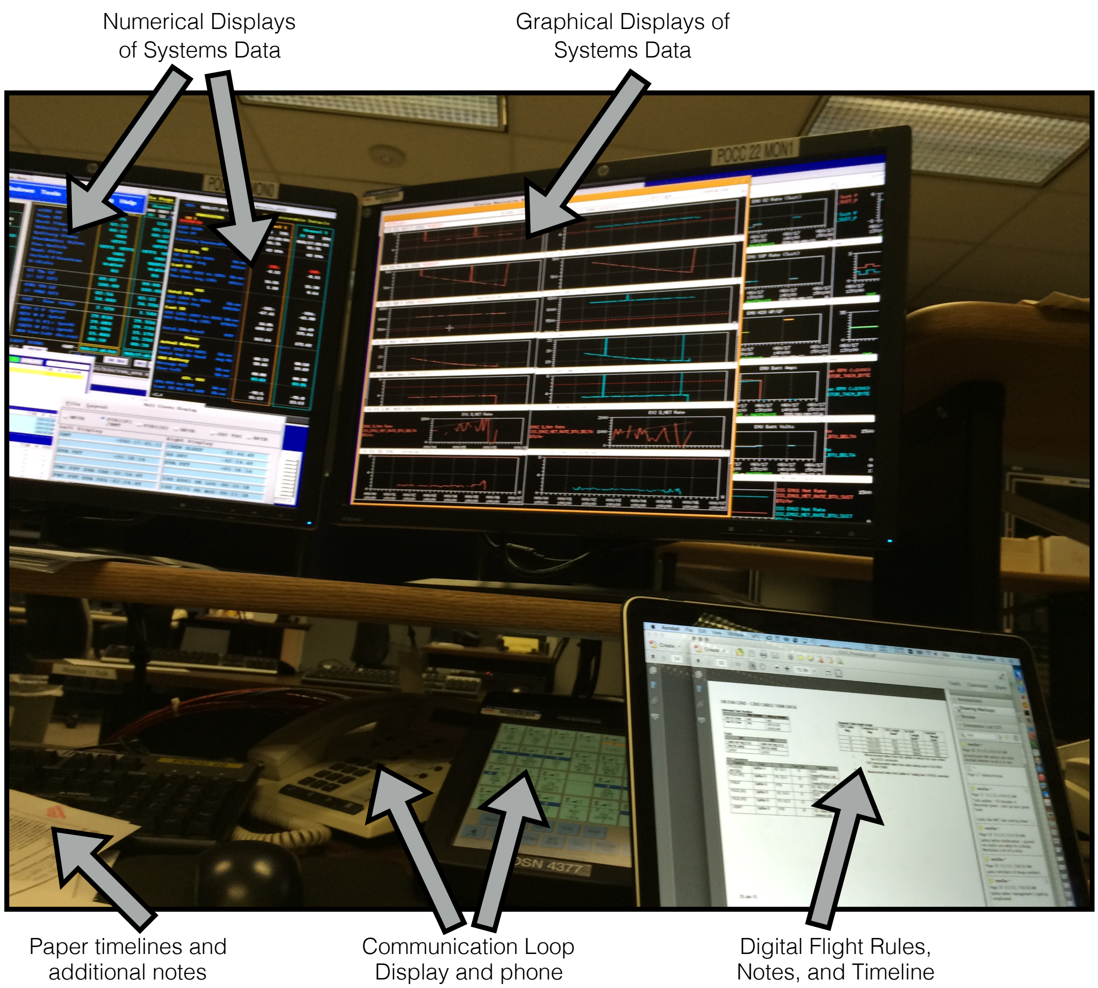



Figure 3.6: EVA multipurpose support room console display example.

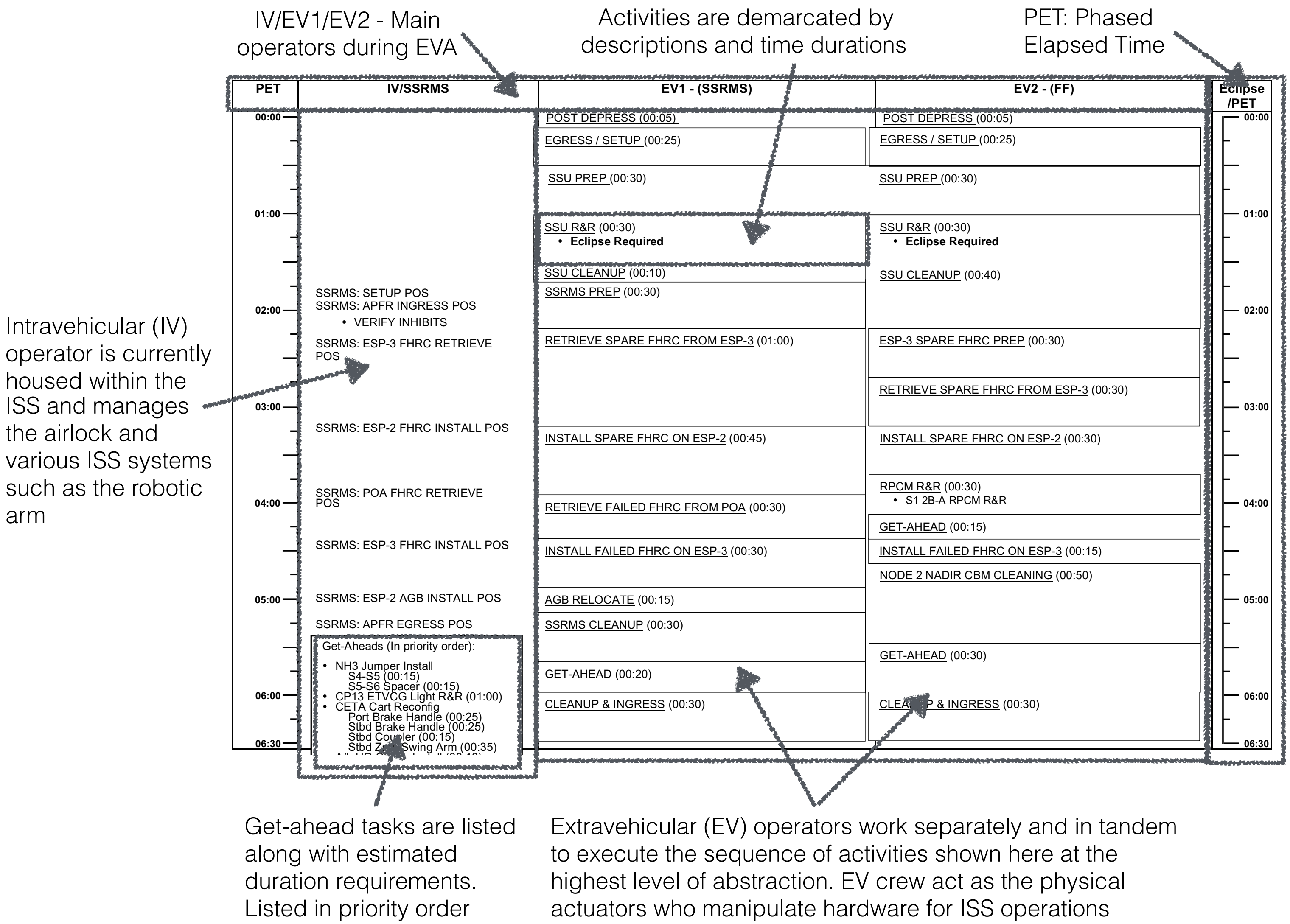



Figure 3.7: EVA summary timeline example with annotations.

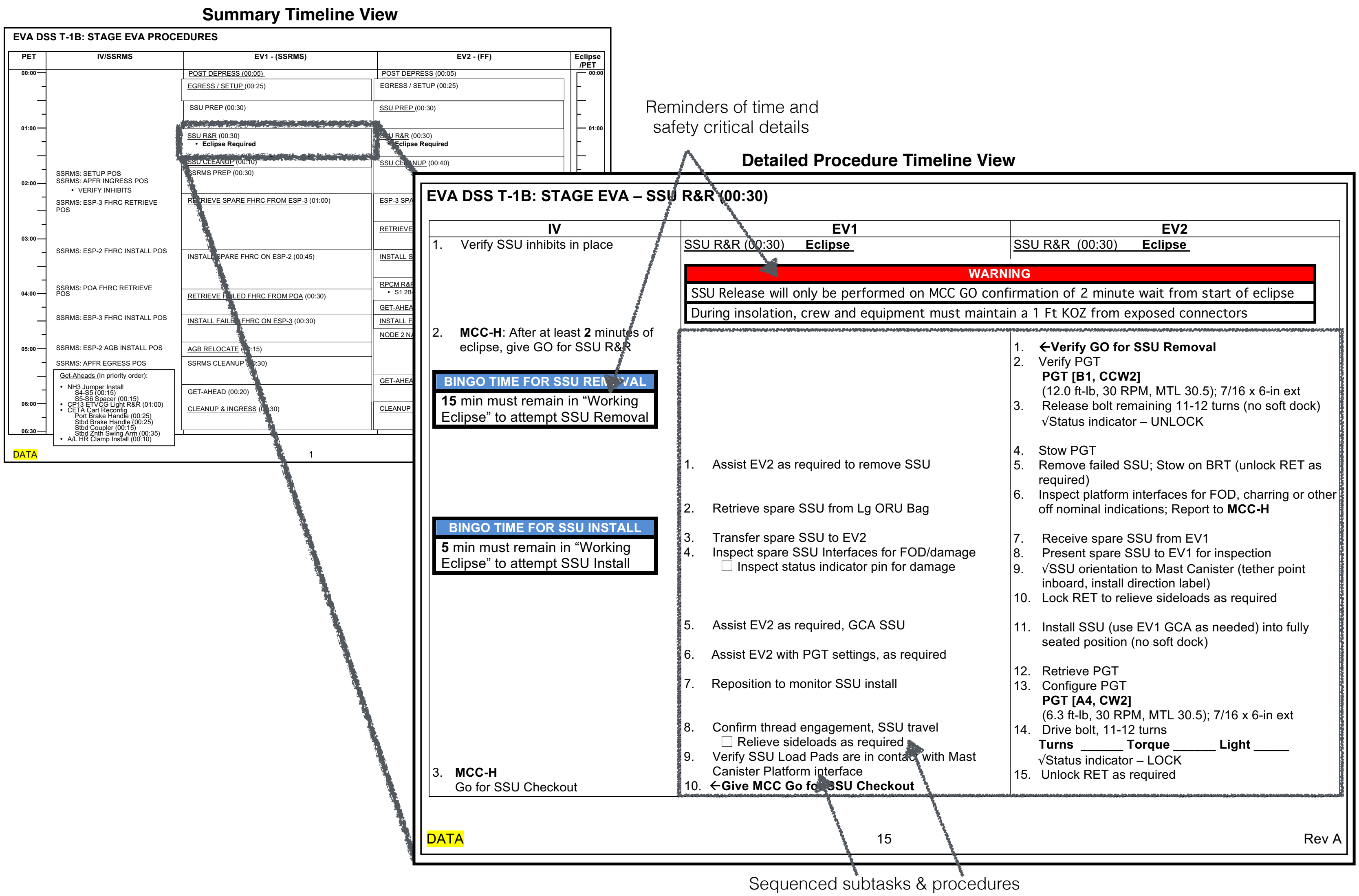



Figure 3.8: EVA summary and detailed procedure timeline example with annotations.

ing that the EVA crewmembers' environment, systems, and tools are operational and safe. The vast amount of domain knowledge that exists within MCC is unlikely to be transferred completely onboard in the near future via automated systems due to technological limitations. Future missions will still require significant human support input into the EVA work domain, and the role of advanced technology in a future time-delayed environment is yet to be determined. Transferring at least some aspects of MCC real-time support capabilities onboard could alleviate some of the time-delay communication challenges between crew and ground.

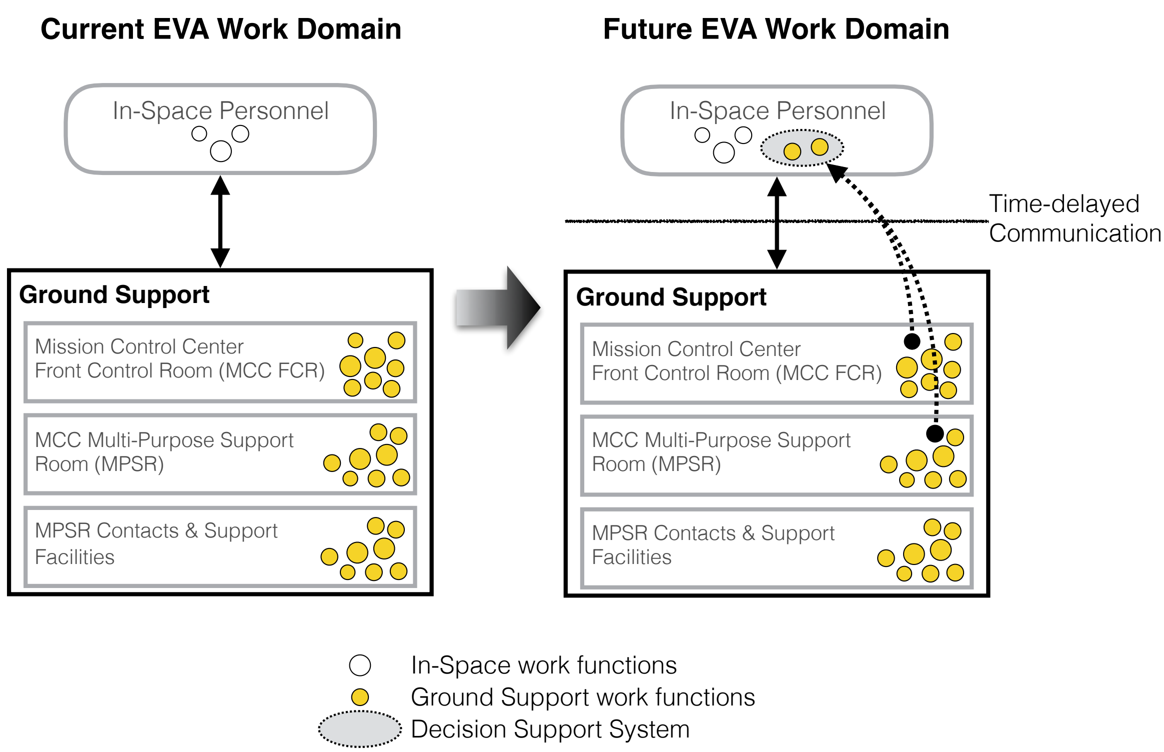



Figure 3.9: Organizational shifts in EVA work domain structure to support future operations with the inclusion of a decision support system for local in-space personnel to support future operations.

As shown in Figure 3.9, how might the transfer of these work capabilities and the resulting work artifacts be transferred to the in-flight crew? In particular, what capabilities do the EVA FCR, EVA Task and Systems operators provide that might be extensible being supported by a support system? To answer those questions, a more detailed analysis of the structure of goals, constraints, and work functions was undertaken.

*EVA Abstraction Hierarchy Models*

Given the complex, distributed operations involved with performing EVA, the AH shown in Figure 3.10 is limited to show functions and constraints present during the execution of an EVA, as opposed to incorporating all the preparatory and post-EVA operations. The question that still remains at this stage of analysis is, what volume of demands exists to currently execute EVA operations?

Figure 3.10 shows the AH pertinent to EVA operations among the EV, IV, and EVA ground support personnel. Almost all operational ownership over each abstraction element is currently retained within mission control. In effect, when considering future operations, implications regarding who has final authority and responsibility over each of these elements must be examined. However, as with many complex work domains, the members and units each have "control over a collection of resources but does not have direct control over the entire work domain (Burns et al., 2005, p. 605)." For example, MCC operators do not currently have any direct control capability over the EV spacesuits. Conversely, while the EV crew have control over their spacesuits, they have limited capability to view and modify the telemetry of their spacesuits. As we aim to build new technological systems for future EVA operations, the appropriate allocation of who (or what) is accountable for the actions assigned to particular operators (or systems) will become more prevalent. At this early stage of domain understanding, the AH models provide a mechanism to first establish what needs to be considered (e.g. constraints, goals, functions etc.) before appropriate allocations can be made.

In addition to the physical and operational constraints, we specifically modeled the EVA environment as shown in Figure 3.12. All members of the EVA work domain must contend with the environmental constraints imposed by both local environments of the EV/IV and MCC, as well as the environment that spans the separation between the operators. While the environment of both the EV/IV crew and MCC are different, each exhibits and imposes similar natural phenomena that can have serious implications for EVA operations, particularly as related to communication capabilities. Each element articulated in Figures 3.10 and 3.12 captures the unique constraints persistent within the work domain. An important contribution of the AHs to this research was to identify these fundamental elements to structure work domain understanding. Each element is intended to be an aggregate representation of the volume of details that must be considered to execute EVA. By obtaining this broad understanding of the domain, I was able to prioritize my research agenda for subsequent analyses within the control task analysis phase. The following descriptions summarize the insights derived from each AH level.

EVA AH Decomposition

Broadly speaking, all EVAs require a common goal or set of objectives that unify all members of the work domain to justify the inherent risks to the crews' lives. In an effort to remain comprehensive in assessing the work domain, the AHs were built to describe the constraints and considerations in the work domain that contribute to the execution of EVA rather than situate their descriptions on any specific EVA objectives. We are trying to understand the intrinsic expectations of the work to be performed during EVA execution. It is not sufficient to understand that we need to insert a power module on the space station for example. Rather it must be understood that everything about that installation process is meticulously planned, tracked, and inspected.

**Functional purposes**: At the root of any EVA is a clear, prescribed set of objectives. Aside from a few Apollo EVAs that emphasized scientific planetary exploration objectives (see Miller et al., 2017a), EVA objectives predominately entail maintenance specific tasks, such as replacing broken hardware and installing new devices. EVA objectives originate, not necessarily from the EVA operators themselves, but rather from NASA program-level directives that involve mission-wide considerations outside the scope of this study. EVA operators must incorporate a priori established objectives and weigh them against crew and

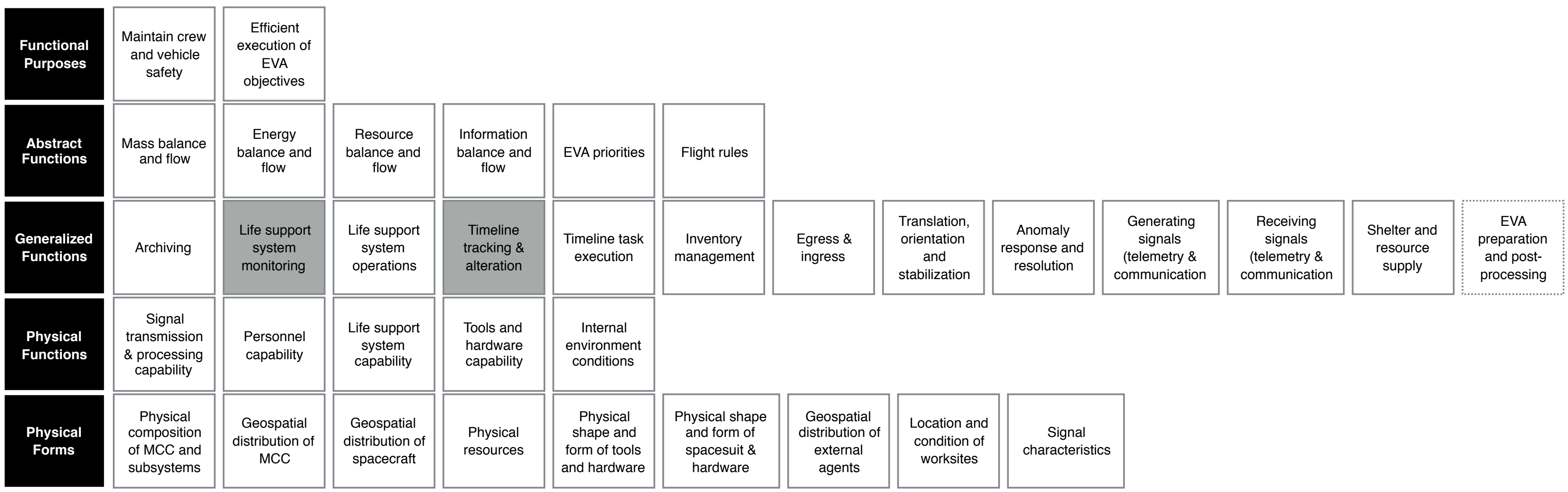



Figure 3.10: Abstraction hierarchy of the extravehicular activity (EVA) work domain that includes EVA-specific mission control, intravehicular, and extravehicular operators. MCC = mission control center (FCR and MPSR Only).

vehicle safety considerations to generate a valid EVA timeline. EVA is considered one of the riskiest activities that an astronaut can perform. Crew safety is the predominant priority during an EVA, and all objectives are considered in the context of the associated ramifications to crew and vehicle safety. Mission control currently plays a vital role in the management and support of balancing timeline execution with crew and vehicle safety. Future EVAs, where time delayed communications will restrict ground input, will need the tools to enable crew to manage these stated functional purposes during execution.

**Abstract functions**: Crew safety and EVA objectives are influenced by the balance of mass, energy, and resources. The spacecraft and external agents are closed systems and are constrained in the physical sense that every single system at the crew's disposal has operational envelopes. Flight rules catalog these critical criteria in the form of if - then and shall/will statements that incorporate factors of safety that further constrain the work domain. Layered within the EVA objectives are preset task priorities and operator preferences that shape how and when particular objectives are executed. Tasks and task sequences are structured in detailed timeline documents that require months, sometimes years, of development and crew training. (See Figure 3.11 for examples of EVA flight rules and task sequences) The distributed nature of the EVA work domain necessitates consideration of information accessibility, synthesis, and utility in the form of various communication modes, such as voice, audio, and text - all of which are constrained by communication transmission coverage, bandwidth, and time delay. Audio is the primary means of communication during EVA execution. Video is preferred but is oftentimes unavailable due to hardware issues or bandwidth/coverage constraints. Resource flow and balance are vital to EVA operations due to the finite resources available for crew disposal; the IV and EV crew cannot use more consumable resources than they have available, particularly regarding life support systems. Energy balance, in this context, pertains to the energy management of the physical systems (power requirements, mechanical/thermal energy management) as well as the energy expenditure of the EV crew. Physical fatigue and metabolic rate expenditure of EV crew are particularly limiting physiologic constraints that affect overall crew safety and objective execution. Finally, mass balance and flow - in terms of the transport and stabilization of external agents and their tools and hardware - also shape how an EVA is executed.

**A15-11** **SAFETY TETHER REQUIREMENTS**

A. AT ALL TIMES DURING EVA, EXCEPT WHEN INSIDE A CLOSED AIRLOCK, EACH EVA CREWMEMBER WILL BE ATTACHED TO THE ORBITER VIA A SAFETY TETHER. FLIGHT-SPECIFIC EXCEPTIONS TO TETHERING TO THE ORBITER WILL BE IDENTIFIED IN THE FLIGHT-SPECIFIC ANNEX. ®[021199-6747B]

*Prevent loss of crewmember and resulting rescue scenarios. For some missions, it may be desirable for the crewmember to be attached (to a certified tether point) to the payload secured in the payload bay rather than the orbiter.*

B. EVA TOOLS WILL BE TETHERED TO THE CREWMEMBER AT ALL TIMES DURING THEIR USE.

*Prevents loss of tools. Free-floating tools could impact orbiter causing orbiter damage.*

| Procedure | Failure | Work-Around Steps |
|---|---|---|
| **GENERIC** | **TA Clamps** | |
| | 1. TA clamps fail to release | A. With handle up, press down on top of rounded clamp<br>B. With handle up, use tether hook to pry drawhook from capture pin |
| | **NZGL Connectors** | |
| | 2. Connector fails to release from softdock | A. Verify bail is in fully demated position (aft)<br>B. Inspect connector/bail for FOD<br>C. Check alignment/side loads/interference<br>D. Wiggle/jiggle connector<br>E. On MCC GO: Use EVA hammer or similar tool to gently tap bottom of connector |

Figure 3.11: EVA flight rule example taken from the Space Shuttle Operational Flight Rules (Top) and EVA task cribsheet example used in the event of procedure issues (Bottom).

**Generalized functions**: The generalized function level provides a decomposition of the main functions required to execute EVA. Many functions at the generalized function level rely on the processes of generating, receiving, and processing signals due to the distributed nature of operators. In raw form, transmitted signals include telemetry data from sensors, as well as audio, video, and text information from the crew. In addition to generating and receiving transmissions, operators must contend with the archiving and management of that data. Present-day examples of this process includes audio transmission that are archived into handwritten and digital flight notes. Processes of inventory management constrain EVA execution by imposing storage, access, and maintenance limitations enforced by the tools and hardware utilized during execution. Processes of translation, orientation, and stabilization require geospatial considerations, such as fields of view, keep-out zones, attachment points, and translation paths. The processes associated with egress and ingress impose a host of physical integration constraints with the spacecraft airlock in addition to health considerations such as decompression sickness. Finally, anomaly response and resolution within EVA operations consist of diagnosis-related constraints, such as the ability to access internal hardware and recover relevant engineering design specifications. The dashed-line element serves as a placeholder of activities performed before and after the execution portion of EVA that includes all the planning, training, and maintenance functions deemed outside the scope of this study.

**Physical functions**: The physical function level encapsulates the functional capabilities of the individual astronaut, spacesuit, spacecraft, tools, and hardware. Currently, limited diagnosis and anomaly response capabilities exist for the EV crew, and mission control is relied upon to monitor each of these domain components. In addition, mission control must rely upon the crew to execute many activities because in some cases no direct manipulation capability, e.g. the spacesuit hardware. Constraints included in the EVA domain also comprise the unique capabilities of the astronauts themselves, in terms of physical endurance and skill sets as well as mental and workload capacities. Additional constraints to consider include internal environmental constraints such as crew comfort and hardware capabilities.

**Physical form**: At the physical form level, constraints result from the geographical distribution of assets, resources, and signal characteristics. The characteristics and content of the transmissions are the only forms of interactions that extend to all EVA operators within the domain, and communication constraints in terms of bandwidth and coverage impose critical limitations on EVA. For example, during present-day EVA operations, if the crew cannot establish audio communication with MCC within 30 minutes of loss of signal, the flight rules dictate the EVA to be terminated. Note that EVA flight controllers within

MCC must rely an other console operators to maintain systems such as the communication system or robotic assets. Those specific MCC interactions are a potential area of future study. The method by which EV and IV crew interact also exists at the physical form level through interfaces between the spacecraft and spacesuit/hardware.

Environment AH Decomposition

Following the example of Burns et al. (2005), the EVA environment was modeled similar to the natural environment found in naval operations because of the profound impact that the environment has on EVA operations. Uniquely, the functional purpose level was not included, because as a natural system, functional purposes are not necessary. The following discussion describes the remaining four abstraction levels for the environment.

**Abstract function**: The measures by which the environment operates follow the forces of nature in the forms of the conservation equations (i.e., conservation of mass, momentum, and energy). The conserved physical quantities impose limitations on the operational capabilities of the engineered systems utilized by the EV and IV operators throughout the EVA.

**Generalized function**: The generalized function level is divided into physical processes that are associated with various environmental properties. These processes include planetary processes such as orbital mechanics as well as solar processes. Orbital mechanics imposes the temporal separation (time-delayed communication) constraint and is a constantly varying phenomenon. Whether in the vacuum of space or on a planetary surface, the EVA work domain is influenced by the presence of electromagnetic radiation from both a crew health standpoint and a signal transmission perspective. Engineered systems also interact with the environment by introducing additional radiation fields as well as potentially harmful contaminants.

**Physical function**: The elements included in the physical function level pertain to the operational environments of the operators' systems. Once beyond low Earth orbit and the protection of the Earth's magnetosphere, solar and extra-solar processes become strong

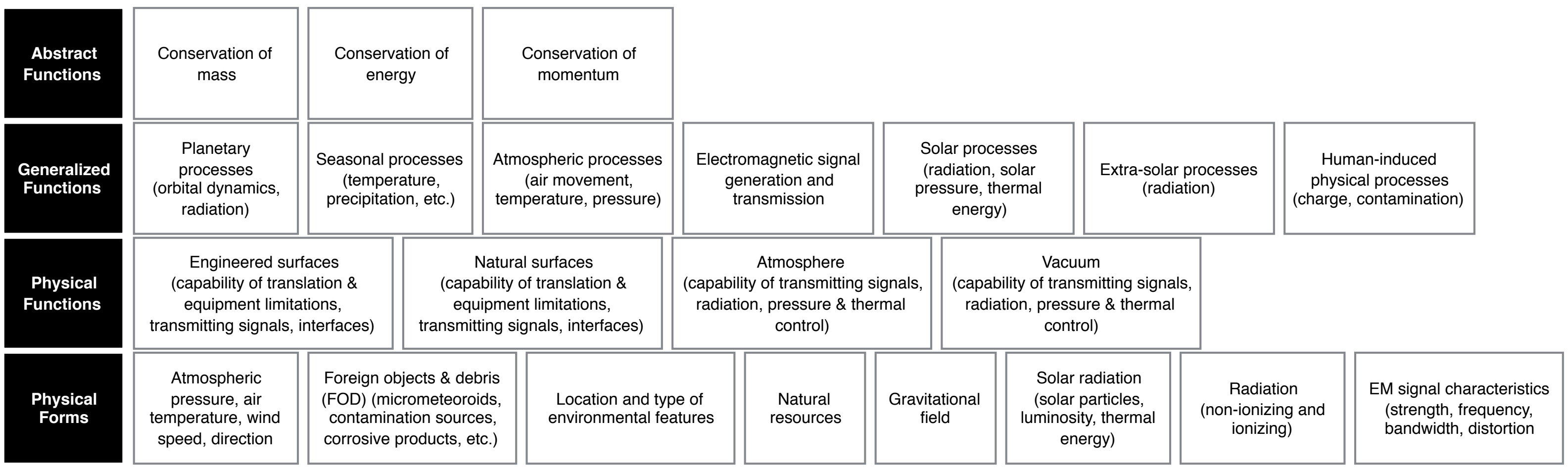



Figure 3.12: Abstraction hierarchy of the extravehicular activity environment. EM = electromagnetic.

physical constraints on crew health and signal transmission capabilities. Earth atmospheric processes also affect mission control's ability to communicate with the crew. EV crew must also physically interact with their environment, which in some cases can be engineered surfaces such as the ISS or natural surfaces like the geologic features of Mars. Each type of surface constrains translation capability and communication coverage and has hardware interface implications.

**Physical form**: At the physical form level, the model delineates elements that are pertinent for EVA operators to collect and monitor. Elements such as terrain layout, radiation levels, and foreign objects and debris are examples of the environmental measures that are useful to EVA operators.

In general, the environment is a source of many constraints for operators to contend with and these elements can have significant influence during EVA. How to sense, assess and incorporate the constraints depicted in Figure 3.12 into future operators will need to be part of the larger design process moving forward. However, this particular component is outside the scope of the remainder of this thesis.

### 3.2.3 WDA DSS Design Implications

At this point in the CWA, the WDA revealed two broad perspectives to described the EVA work domain as stated below. From a system designer's perspective, the opportunities for technological development within the EVA domain are vast. The individual elements displayed in Figures 3.10 and 3.12 must, at a minimum, be supported to ensure successful future EVA operations. At this point in the analysis process, I have made no assumptions or proposed any technological design solutions. Instead, I explored and captured a broad understanding of the volume of constraints that shape EVA operations. This inventory of work domain operators, goals, and constraints now enables the design process to be scoped in a variety of ways: 1) The specific operators identified in the information flow model can be examined in more detail with more targeted analyses (e.g. the Control Task Analysis),

2) specific constraints and work functions can be prioritized for additional investigation, and 3) the design process can be situated within the larger body of design initiatives.

| |
|---|
| Perspective 1: EVA operations is a tightly choreographed endeavor that involves a multitude of personnel. Information exchange between the entire EVA team is critical to convey accurate EVA state information. The in-flight crew are particularly reliant on the wealth of operational and engineering insight that currently resides with MCC to accomplish EVA objectives. |

| |
|---|
| Perspective 2: The reallocation of generalized work functions identified in Figure 3.10 among the EVA operators will be required for future EVA operations. The challenge is how to systematically reassign those functions and seek DSS designs that could enable that transition. |

Two high-priority general work functions were identified for further investigation in the Control Task Analysis (ConTA): (a) life support system monitoring and (b) timeline tracking and alteration. These two functions emerged due to a number of motivating factors. The information flow model revealed that two teams of EVA personnel (EVA Task and Systems) in MCC are dedicated to performing these two work functions. In collaboration with the EVA front room controller, aspects of timeline and life support system management are integrated with EV crew action throughout execution to enable successful EVA operations. When weighted against the remaining general work functions shown in Figure 3.10, these two functions have significant impact to EVA safety and productivity, independent of the particularities of specific hardware or tools. The other work functions do warrant investigation, but they are dependent on a multitude factors that do not yet exist or not readily accessible (e.g. future spacecraft, spacesuits, hardware, communication infrastructure, and other groups of MCC personnel outside of the EVA flight team). Additionally, time delayed communications in a future context will likely impeded MCC's ability to perform these functions (e.g. provide timely, relevant, and actionable information to the EV crew during execution). Therefore, the scoping design consideration was to dedicated DSS development efforts towards life support system and timeline management functions.

*The Impact of Time-Delayed Communication on Generalized Functions*

At this point in our EVA work domain understanding, it can be difficult to predict the extent to which time-delayed communication will impact the generalized work functions shown in Figure 3.10. The extent to which these functions must be transferred from MCC to crew to manage locally will be a function of the communication environment they operate within as well as the temporal dynamics of the functions themselves. In other words, time critical functions will be more immediately impacted by time-delayed communication as compared to others. For example, life support system monitoring and timeline tracking and alteration can have immediate impacts on crew actions, so even communication delays on the order of seconds or minutes can have profound negative impacts. Others like inventory management and archiving might not need to be completely restructured in order to facilitate until longer time-delay environments are reached. Table 3.3 shows an initial depiction of when specific work functions will likely become significantly impacted by time-delayed communications. There will be a host of challenges in facilitating the transition of all these work functions for the crew to manage locally and I contend that once the crew reach destinations where communication delay is on the order of minutes, all generalized work functions will need significant restructuring to ensure mission success.

Table 3.3: Impacts of time-delay communication on generalized work functions.

| | Communication time-delay scale | | | | |
|---|---|---|---|---|---|
| | Present-day | | | | Deep-Space |
| Generalized Work Function | <O(seconds) | O(seconds) | O(minutes) | O(tens of minutes) | >O(tens of minutes) |
| Archiving | | | Significantly Impacted | | |
| Life support System Monitoring | | Significantly Impacted | | | |
| Life Support System Operations | | Significantly Impacted | | | |
| Timeline Tracking & Alteration | | Significantly Impacted | | | |
| Timeline Task Execution | | Significantly Impacted | | | |
| Inventory Management | | | Significantly Impacted | | |
| Egress & Ingress | | Significantly Impacted | | | |
| Translation, Orientation, and Stabilization | | Significantly Impacted | | | |
| Anomaly Response and Resolution | | Significantly Impacted | | | |
| Generating Signals | | | Significantly Impacted | | |
| Receiving Signals | | | Significantly Impacted | | |
| Shelter and Resource Supply | | | Significantly Impacted | | |
| EVA Preparation and Post-Processing | | | Significantly Impacted | | |

*Work Domain Analysis Summary*

In summary, the WDA synthesized the EVA work domain to identify and prioritize potential avenues for DSS development. At the onset of a design project, there is a design tendency to make assumptions about the purposes and potential end users of the envisioned system without fully considered the current state of affairs. But while the introduction of advanced technology in undoubtedly warranted, the WDA provides a mechanism to identify when it will be most useful. We demonstrated that by leveraging the WDA, the AHs articulated the elemental functions and constraints that influence and shape EVA execution. From this synthesis process, we identified a potential DSS design pathway to provide local life support and timeline management capabilities. The emphasis is made on a tactical support because the dynamics of an EVA can change suddenly, which will force EV crew members to respond appropriately, in the absence of immediate mission control input (due to the time delay in communication). Primary support functionality of an EVA DSS was identified from the generalized function level as two complementary components: (a) life support system monitoring and (b) timeline tracking and alteration. While the current EVA literature primarily emphasizes development of the hardware that EV operators may need in the future, this chapter conveys the breadth of constraints and goals that shape EVA operations and where where additional research should be dedicated.

In the next section, a control task analysis for the two generalized functions identified here is presented and linked to DSS design requirements.

## 3.3 Control Task Analysis

### 3.3.1 ConTA Methods and Models

The Control Task Analysis (the 2nd phase of CWA)(ConTA) was performed to further refine EVA understanding by investigating a specific subset of generalized work functions identified in the WDA. Two model types - a contextual activity template (Naikar et al.,

2006) and decision ladders aggregated with details from multiple CSE sources (Bisantz and Burns, 2009; Jenkins et al., 2011; Rasmussen, 1986; Vicente, 1999) - were built to articulate SME insight and translate that into high level design requirements. Furthermore, this effort reinforced the need for support development regarding life support system and timeline management functions.

The contextual activity template (example shown in Figure 3.13) decomposes the work functions along the vertical axis and operational phases along the horizontal axis (Naikar et al., 2006). The circles/whiskers and dashed boxes delineate the typical and potential associations that each work function has with each operational phase, respectively (Stanton et al., 2013). From this template, the execution of work functions were mapped to the prototypical operational phases of the EVA work domain to convey when the operators faced the variety of cognitive demands on domain operators.

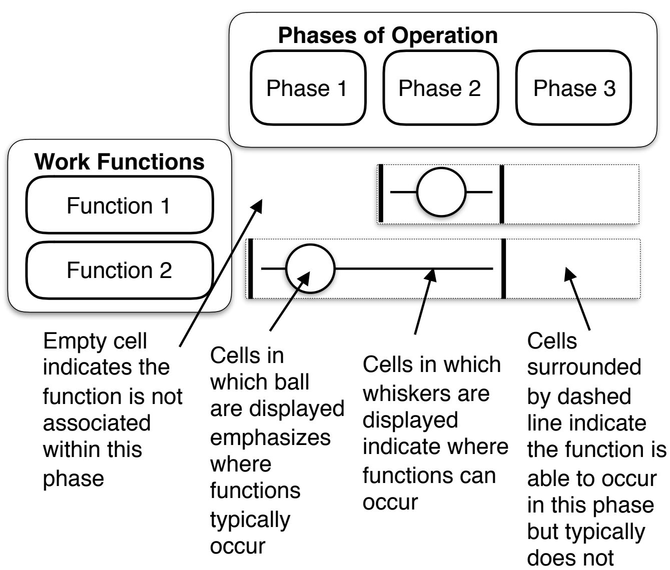



Figure 3.13: Control Task Analysis activity template example (Jenkins et al., 2008a).

Following the styles of Vicente and Bisantz, two decision ladders were constructed for two generalized work functions: (a) life support systems monitoring and (b) timeline tracking and alteration. The decision ladder depicts, as shown in Figure 3.14, the linear sequence of events that links various information-processing stages with resulting states of knowledge (Vicente, 1999). A novice usually steps through each rung in the ladder sequentially whereas an expert may leap or shunt to subsequent data-processing or states of knowledge based on their prior experience or understanding of the system. For completeness, SMEs were interviewed regarding all states of knowledge. Presenting a variety of decision ladder-stage descriptions promoted consistent data collection and stimulated knowledge elicitation during interview sessions. Rather than focus on the data-processing activities themselves depicted as rectangles, I emphasized the expected states of knowledge (SoK) (denoted as circles) from the perspective of current-day SMEs. SoKs are emphasized because these elements represent current EVA work domain characteristics likely extensible to future EVA operations. The data-processing activities were omitted because those processes are inherently tied to present-day tools and technologies. The goal at this stage in the CWA process is to not prescribe how a DSS might work but rather establish the purposes and requirements for a DSS to support the specified SoKs.

The requirements definition process leveraged the SoKs generated from the decision ladders to generate two forms of requirements: Cognitive work requirement (CWR) and Information relationship requirements (IRR) as described below:

- **Cognitive Work Requirement:** Specifies the cognitive demands, tasks, and decisions that arise in the domain and for which the operator requires support.
- **Information Relationship Requirement:** Specifies the proper context for the required data, turning it into information that the decision maker requires.

These two types of requirements followed prior work by Potter et al. (2007); Elm et al. (2003) that also attempted to use CWA to derive requirements for a DSS. What sets my work apart from prior work is that I more directly link the Decision Ladder model insights with the specification of requirements, rather than apply a modified, boot-strapped work domain methodology, which has seen little traction within the larger design community. In doing so, I was able to facilitate a traceable process for requirements definition, where the source motivations for those requirements are grounded in the work demands present in the EVA domain. Each SoK insight identified from the decision ladder was first rewritten

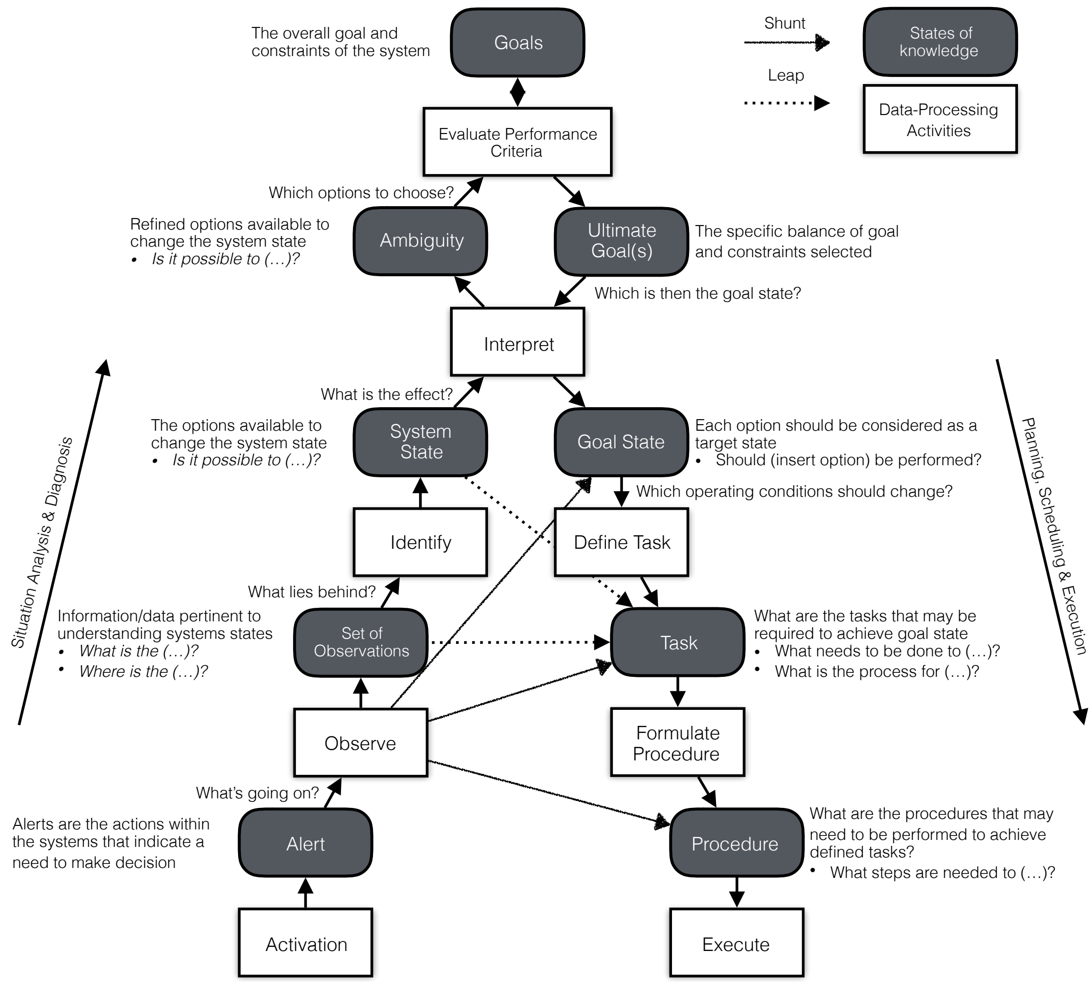



Figure 3.14: Control Task Analysis activity template example.

in the form of at least one CWR statement and then subsequent IRR statements were generated to convey the information associations required to address their respective CWRs. Supplementing each CWR and IRR pair was a requirements intent description to provide additional context and further explain particular aspects of the requirements set.

Figure 3.15 shows an example of the linkages connecting SME states of knowledge to their resultant requirements and intent descriptions. This process was performed for all decision ladder states of knowledge. The specific phrasing of the CWR and IRR statements aimed to meet three primary objectives: (1) to capture the intent of the associated SMEs SoKs, (2) to fulfill the basic definitions of CWR and IRR statements as previously defined, and (3) to meet the minimum standards of SE requirements quality as defined by Turk (2006). The specific phrasing was iterated upon with SMEs throughout the development process to yield a final requirements document associated with each decision ladder found in Appendix A.2.

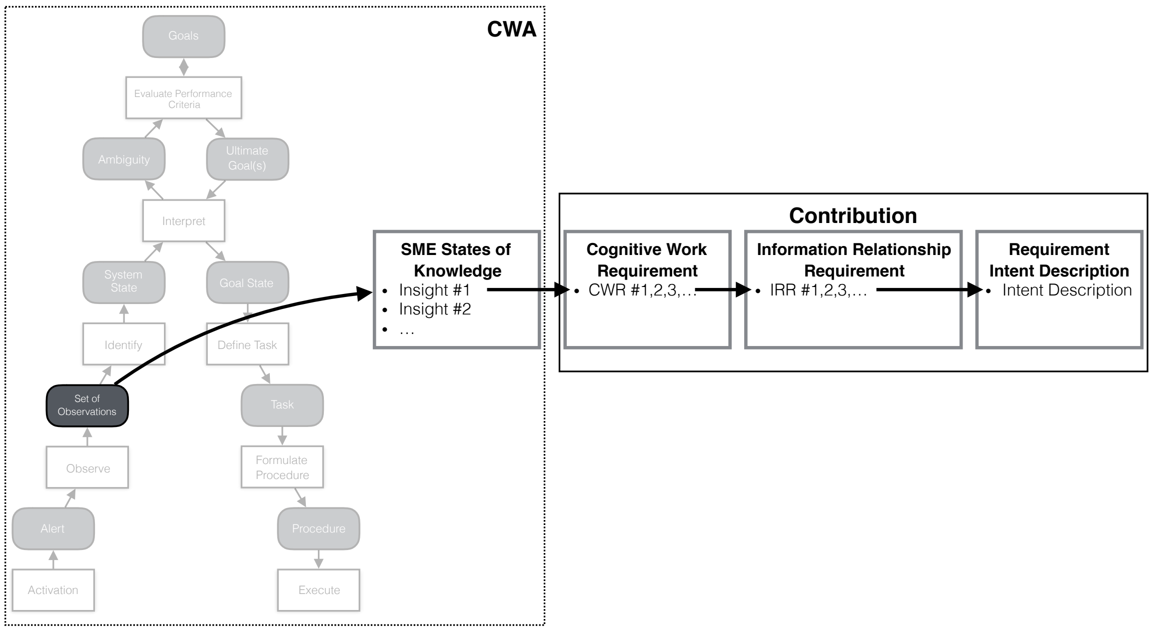



Figure 3.15: Control Task Analysis - Decision Ladder and Requirements Derivation Process.

The development of each of ConTA model and requirement set was based on a series of observation sessions and semi-structured interviews with certified EVA flight controllers (EVA front room controller, systems, and task positions, as shown in Figure 3.4). Following initial observation sessions of two ISS EVAs and a simulation EVA, a preliminary contextual activity template and decision ladders with requirements were generated. Subsequent follow-up observations and interviews were used to refine the models and to validate model content. In total, >29 hours of interaction with and observation of EVA flight controllers beyond the WDA model development efforts were completed for this portion of the study. Figure 3.4 summarizes the time spent observing, interviewing, and validating the resultant ConTA models and requirements.

The remainder of this chapter describes the analysis and synthesis stages of life sup-

Table 3.4: Control Task Analysis (ConTA) model development process.

| ***Timeline*** | **Observation** | **Interview** | **Model** | **Validation** |
|---|---|---|---|---|
| 2/25/15 | ISS Increment 42 EVA 30 (8 hr) | | | |
| 3/1/15 | ISS Increment 42 EVA 31 (7 hr) | | | |
| 4/24/15 | Mock EVA Simulation (7 hr) | | | |
| 5/1/15 | | ◯ | Preliminary ConTA models developed | |
| 5/6/15 | | ◯ | | |
| 6/11/15 | | ◇ | | |
| 6/12/15 | | ◇ | | |
| 6/15/15 | | ◇ | | |
| 7/6 - 7/7 2015 | | ◇ (split over two days) | Preliminary requirements developed | |
| 7/8/15 | | ✔ | | |
| 7/10/15 | | ◇ and ✔ | | |
| 11/19 - 11/20 2015 | | ◇ (split over two days) | | |
| 7/12/16 | | ◇ and ✔ | | |
| 7/19/16 | | ◇ and ✔ | | |
| 7/26/16 | | ◇ and ✔ | | |
| 7/28/16 | | ◇ and ✔ | | |
| 8/3/16 | | ◇ and ✔ (1.75 hr) | | |
| 8/5/16 | | ◇ and ✔ | | |
| 8/19/16 | ISS US EVA IDA2 Install (7 hr) | | | |
| 6/12/16 | | ◇ and ✔ | | |
| 1/27/17 | | ◇ and ✔ (2 hr) | Final ConTA models & requirements developed | ✓ |
| 2/27/17 | | ✔ | | ✓ |
| 5/26/17 | | ✔ | | ✓ |
| Totals | 29 hours of in-person ISS EVA operations | 22 hours of model/requirements review interviews | 1 Activity Template, 2 Decision Ladders & >90 Req. pairs developed | |

| **Legend** |
|---|
| ◯ EVA Sim Follow-up with SME (1 hr) |
| ◇ ConTA Model Review with SME (1 hr) |
| ✔ DSS Requirements Review with SME (1 hr) |

port system management and provides exemplars to articulate the requirement derivation process. The full decision ladder and requirements set for both the life support system and timeline management functions along with appropriate interview protocols and materials can be found in Appendix A.2.

### 3.3.2 ConTA Modeling Results and Requirements Derivation

*EVA Contextual Activity Template*

The EVA work domain, as shown in Figure 3.16, is decomposed into an allocation matrix that associates prototypical EVA phases of operation with EVA generalized work functions identified from Figure 3.10. Along the horizontal axis, the EVA work domain is composed of 11 distinct phases of operation that span the entire execution portion of EVA. The *pre-EVA* and *day-of-EVA preparation* phases refer to all planning, training, and preparatory stages required to perform EVA, which can begin up to 1 to 2 years prior to EVA execution. This study is dedicated to EVA execution, rather than the lengthy EVA planning processes, because the execution component of future EVA will likely be most affected by time-delayed communications. *Airlock operations* refers to the activities performed within the airlock, which can include the crew being suited or unsuited. The shaded region signifies the operational transition from spacecraft life support to spacesuit life support, which officially signifies the start of EVA execution.

The astronauts then enter the *egress* phase of operations to exit the spacecraft with their tools and hardware. Once egress is complete, the crew then cycle between the operational phases of being *stationary* and *in motion* to travel between and within the target worksites. While at a worksite, the crew then cycle through a series of phases that consist of *worksite setup*, *task execution*, and *worksite cleanup*. In terms of tasks, the crew can be working on *objective tasks* (those that support the EVA timeline objectives) or *other tasks* (those not critical to EVA goals). An example of other tasks includes rest periods or scenic photography. Once all objectives of the EVA are met, the crew *ingress* and then enter the *post-EVA* operational phases.

The EVA work functions generated from the WDA are shown along the vertical axis and describe the set of activities to be performed to conduct an EVA. Two work functions in particular - (a) process of life support monitoring and (b) process of timeline tracking and alteration - are imperative to successful EVA execution and are expected work functions throughout each phase of the EVA. Each minute of an EVA is planned to a prescriptive timeline that directs task execution; however, EVA execution is a dynamic process that rarely maintains nominal timeline operations. In fact, out of the 391 EVAs performed up to July 27, 2016, 110 (28%) experienced significant incidents, such as systems issues (e.g. system failures), operational incidents (e.g. incorrect task execution), and inadver-

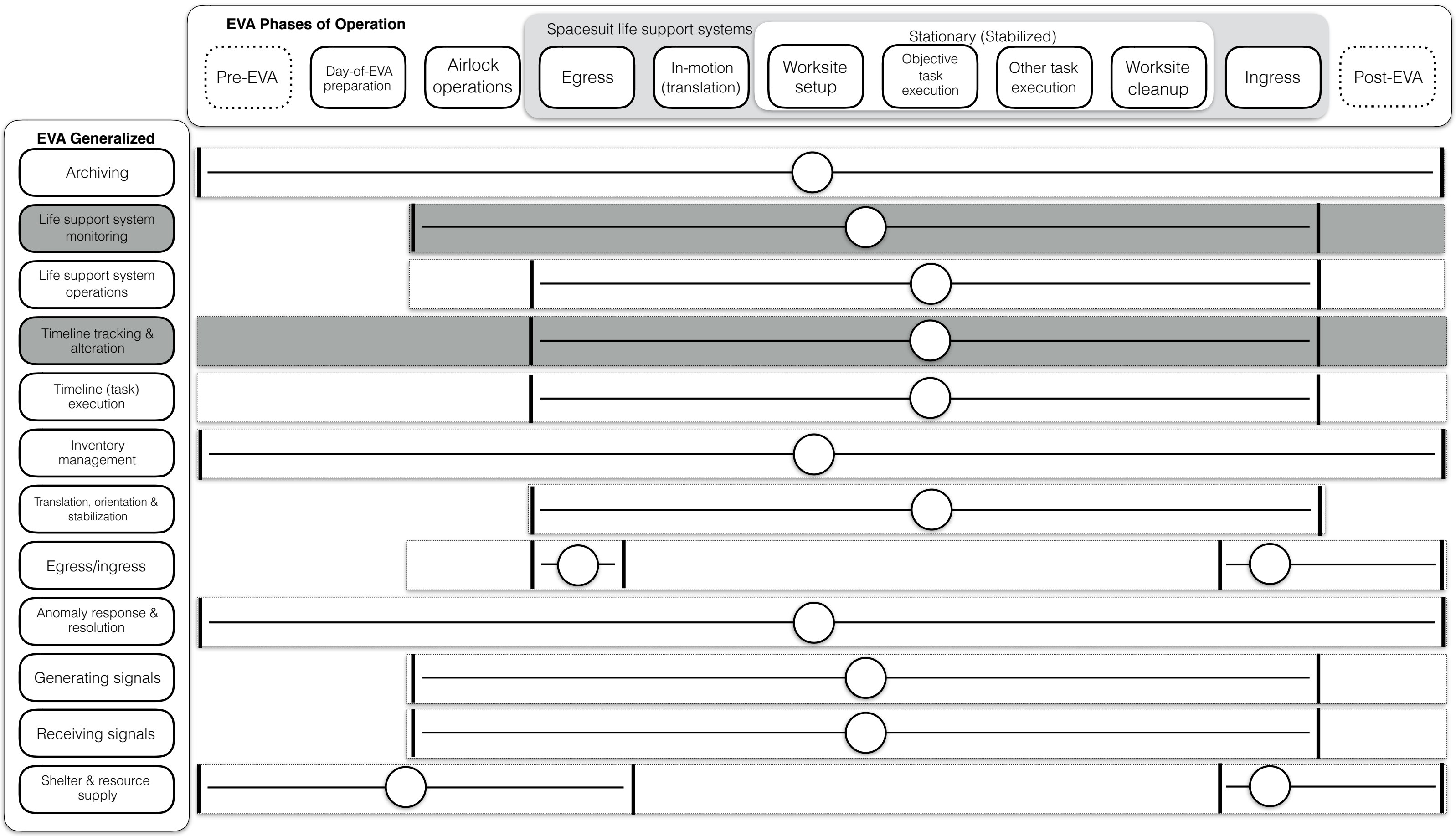



Figure 3.16: Extravehicular activity (EVA) execution phase contextual activity template.

tent releases (e.g. accidentally discarding a tool that is no longer recoverable) that caused a timeline deviation (Packham & Stockton, 2017).[1] An EVA timeline must be constantly assessed throughout the duration of and transition between phases specified in Figure 3.16 due to potential fluctuations in task execution and life support system performance. Underlying the execution of EVA is the notion that every task is performed within affordances provided by the life support systems. Operationally, knowledge of the life support system performance across the various operational phases is paramount to maintain crew safety, and significantly influences potential timeline alterations due to the overhead required to maintain the life support systems.

The consideration of any design must account for the mapping between work demands and phases of operation. The contextual activity provides such a mapping to build operational context. The model provides a detailed account of the various phases of operations as they exist today, independent of time or a particular objective and how they related to the generalized functions derived from the WDA. This mapping plays a particularly important role in developing relevant simulation components as part of the envisioning process of the future work domain as discussed in Chapter 5. However, a more in-depth understanding of the decision making processes involved in performing the generalized functions is still required for adequate requirements specification.

*EVA Decision Ladder - Life Support System Monitoring*

Figure 3.17 shows a partial decision ladder with the primary goal of maintaining a safe life support system configuration to enable EVA operations. Starting at the bottom left of the decision ladder, we highlight important SME insights captured in each knowledge state of the decision ladder in the following subsections. We address each SoK in turn as we traverse a portion of the decision ladder in the remainder of this section. The shaded SoKs are carried through the subsequent section to convey the requirements generation process.

[1] An interactive tool to explore EVA significant incidents can be found at: https://spaceflight.nasa.gov/outreach/SignificantIncidentsEVA/index.html

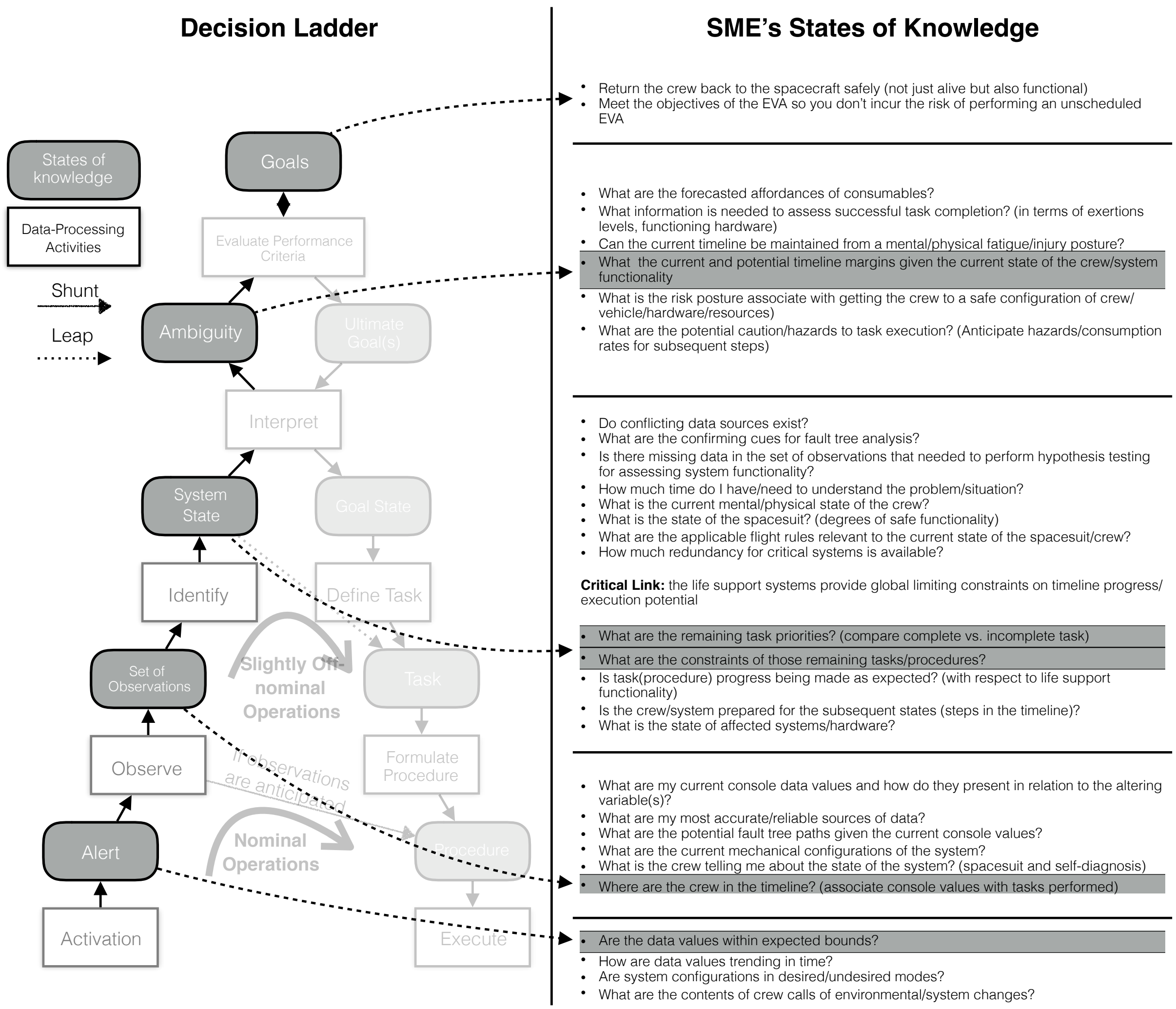



Figure 3.17: Schematic of the decision ladder specification process. Includes a representative sample of the specification of subject matter expert's SoK from Decision Ladder States.

***SoK: Alert:*** The alert state consists of two main sources: (a) suit telemetry and (b) the EV crew members. The suit telemetry consists of data streams from sensors inside the space suit that provide insight into the operational status of the various subsystems and level of consumables. In raw form, the telemetry of the current ISS EVA spacesuit consists of >60 unique pieces of sensor information and 14 spacesuit configuration states per crew member. Each data stream value has associated upper and lower limits. For brevity, we do not specify all the details of the components that constitute spacesuit subsystems and telemetry but rather use the term life support system to refer to those terms collectively. During EVA execution, the time series evolution of the data values, or data trending, dictate what activities are possible based on life support limits. Unfortunately, the data trends, especially for the consumables data, are difficult to accurately forecast, as they are influenced by the metabolic rates of the crew members, which can vary as they perform tasks. Additional alerting features stem from the crew member inside the spacesuit, who uses his or her physiologic senses to describe the operability of the suit. Examples of alerts that can be sensed by the crew members include changes to pressure, temperature, and humidity. Each EVA is unique, and only by understanding the real- time data values can EVA timeline alterations be made safely.

***SoK: Sets of observations:*** The goal at this stage in the decision ladder is to gather information to generate sets of observations regarding the life support system. Sets of observations include consumable estimations, data accuracy considerations, fault tree generation, and timeline task associations. The core set of consumable values needed to maintain the life support system includes oxygen, secondary oxygen, battery, and water. The consumables are viewed in multiple forms (time series, averaged, and filtered), which are used collectively to estimate a total operational time remaining or affordance for each consumable. Both the spacesuit and the console systems independently synthesize raw suit telemetry data to generate an estimate of the state of the life sup- port system. Due to the restrictions or limitations in information transmission, the raw data may be incomplete or corrupt, prompting ground operators to assess the validity of the presented data before any conclusions can be made. In addition to consumable calculations, spacesuit telemetry data convey information regarding the functions of the various subsystems. In the presence of a spacesuit hardware alert, operational fault trees are commonly generated to establish a diagnosis path to isolate and confirm the source of the alert. This process requires an intimate knowledge of the subsystem components and their interdependencies. Additionally, temporal timeline awareness must be applied to understand the telemetry values. Understanding the tasks performed as they relate to life support data is a critical SME SoK to support.

***SoK: System state:*** At this stage, the set of observations is synthesized to estimate the consumable and physical state values of the suit. Deconflicting data trends and identifying confirming cues play an important role in diagnosing the system state. Knowledge of the redundancy levels for each subsystem is also incorporated into state understanding. Again, life support monitoring is integral to the successful execution of the timeline, and so timeline tracking and alteration are important considerations with life support system state estimation. Anticipatory knowledge of upcoming tasks is also incorporated into system understanding to forecast potential affordances or issues.

A critical link within the EVA work domain was identified at this stage of the analysis: Life support systems provide the global limiting constraints on timeline progress and execution potential (barring any unforeseen systems failures). As highlighted, the synthesis of timeline data with life support system data is critical to supporting the overall EVA execution.

The implication of this insight is that to formally link life support system constraints to EVA operations, explicit awareness of the timeline task data must be incorporated into the DSS. Currently, the timeline exists in static paper-based formats. Therefore, present-day EVA operators (EVA TASK and SYSTEM controllers in Figure 3.4) meticulously link timeline task details and EVA telemetry data manually, relying on practice and expertise alone to manage associations and implications.

***SoK: Ambiguity:*** Many sources of ambiguity exist within the data synthesis and interpretation process related to the spacesuit. Ambiguity is typically assuaged by generating a comprehensive list of *what-if* scenarios, many of which are formulated a priori to EVA execution. The scenarios incorporate potential implications to the physical subsystem performance, as well as contingency procedures in an attempt to remedy or "safe" the system configuration. Of course, a priori consideration of failures is limited by the imagination of the operators to conceive system deviations. Another source of uncertainty resides with the metabolic rates of the crew members and how those rates can influence the life support system. The goal is to ascertain how much timeline margin the life support system can provide; however, that margin is highly predicated on how the crew members are performing the EVA in real time. Furthermore, ambiguity is generated from the unknown unknowns with regard to potential hazards and system sensors. As it currently stands, EVA practitioners must extract operational knowledge from a limited set of sensors, with uncertainty in their measurements and with uncertainty in their measurements validity.

**SoK: Goals.** The highest-priority goal is to keep the crew alive. If there is any indication that crew life is imminently threatened, all resources and attention are dedicated to ensuring crew safety. Aside from immediate life-threatening events, the EVA goals shift to increase timeline productivity, which manifest as potential timeline alterations become feasible or necessary. In traditional SE requirements documents, requirements or groups of requirements are often summarized by primary or secondary functional objectives (NASA, 2007).

The full set of requirements and decision ladder models are beyond the scope of this chapter and are contained in Appendix A.2 for completeness. The following section describes a subset of requirements for demonstration purposes.

*EVA DSS Requirements Derivation*

Figure 3.15 shows the incremental steps taken to translate the SoK insights to DSS requirements. Each SoK was assessed in relation to the definitions of CWR/IRR and then formatted to meet traditional systems engineering requirements specification. The content and diction surrounding each SoK and Requirement set was then iteratively refined via SME interviews where each statement was assessed. A subset of the resultant requirements are shown in Figure 3.19. For discussion purposes, we focus on the SoK highlighted in the Set of Observations.

As stated, EVA flight controllers are continually gathering observations necessary to understand where the crew are in the timeline. Therefore, the resultant CWR reflects this goal by stating that a future DSS system shall estimate the location in time and space of the EV crew in relation to the planned timeline from a life support system perspective. Subsequently, the DSS will be required to associate the performed and current LSS demands with planned/expected performance from the planned timeline. Given that this particular requirement set is within life support system monitoring decision ladder, these requirements should be considered with that overall intent. The resulting intent description associated with this CWR/IRR pair is shown below as a supplemental material provided along side each requirement. These descriptions summarize the discussions from SME interviews as well as attempts to provide clarification regarding requirement applicability and overall intent.

> The timeline assumes the life support system can support those specific actions. Elements to consider here include: "Is what the crew are doing causing the LSS state changes? If so, are we happy with these changes in the moment?" These requirements convey the importance of associating LSS data observations with as-performed tasks to know if the data presented is reasonable and acceptable. (e.g. Does the metabolic rate for this crewmember seem higher than it should

be, given the specific actions of the crewmember?)

The SoK statements themselves were prompted and derived using existing decision ladder model materials. They were generated both by the researcher and SMEs throughout the model building process and iteratively refined and assessed by SMEs until steady state was reached (e.g. no new insights were being revealed in the interviews). Figure 3.18 shows the process by which the CWR and IRR states were generated initially by the research practitioner following the requirements defined by both Elm and Turk. Elm definitions aim to capture work context whereas Turk definitions aim to align the statements with the traditional systems engineering process.

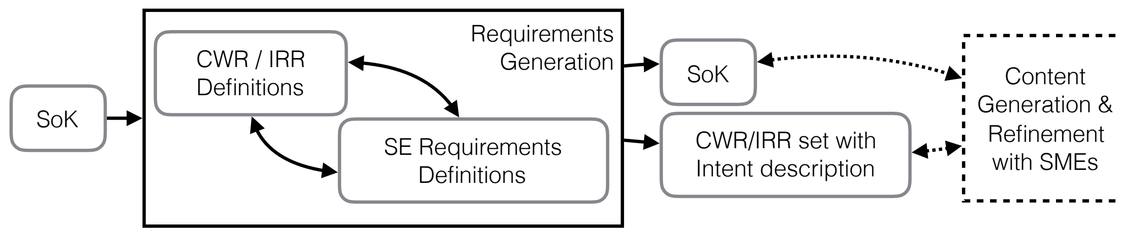



Figure 3.18: Requirements generation process.

The Intent Descriptions summarize much of what was talked about regarding each requirement pair. I found that including direct quotations where appropriate help to focus my descriptions. Having a list of SoKs helped focus the discussion surrounding the requirements. It is easy to get off topic or create duplication which is why I first emphasizing getting a full set of SoKs. Subsequently, I generated a preliminary set of requirements. Then, I interviewed SMEs to discuss and iterate on the content which yielded content refinement and context rich intent descriptions.

Figure 3.20 shows the final set of prioritized requirements. Within each decision ladder stage, the requirements were weighted against each other based on relative importance and estimated level of complexity to satisfy. As a result, each requirement was categorized into one of three levels of consideration: 1) immediate, 2) near term and 3) long term future. Based solely on my understanding. From the CWA process, it became clear

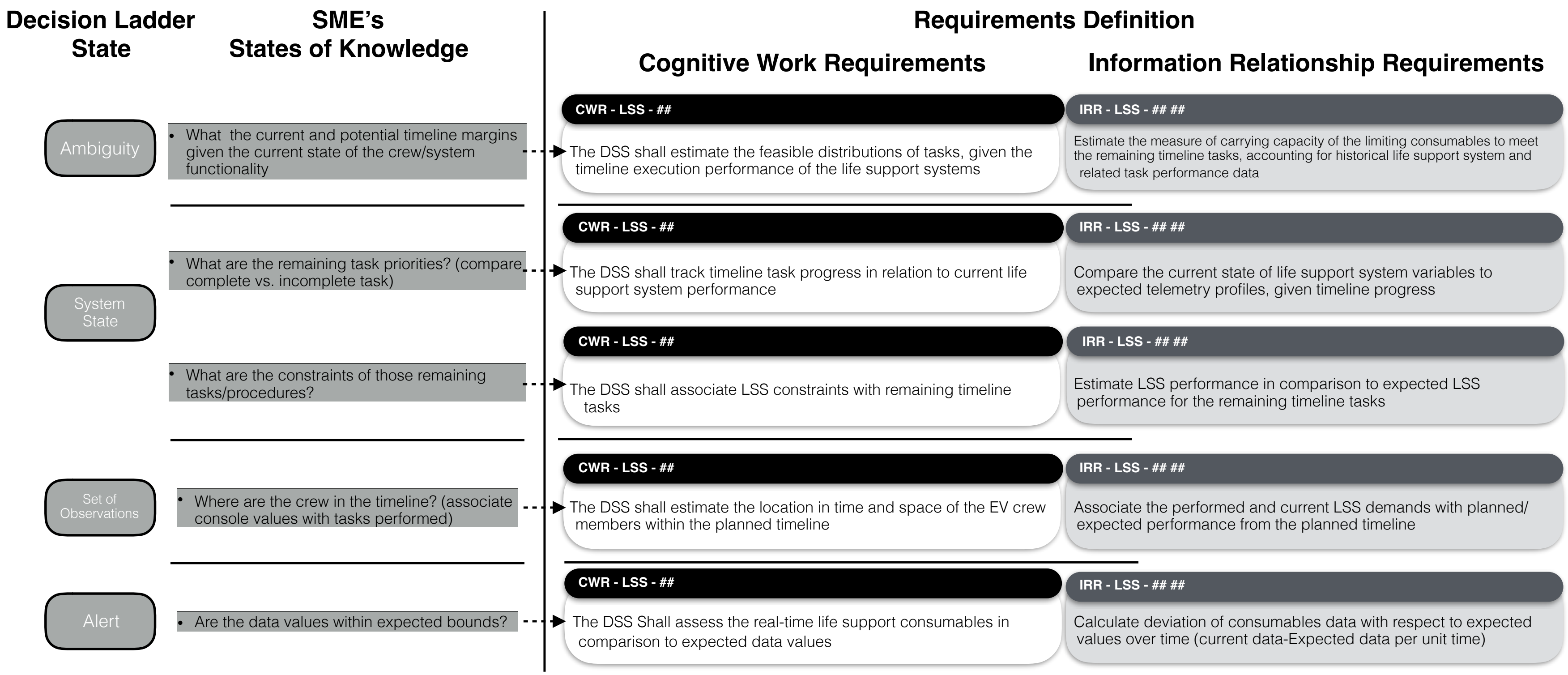



Figure 3.19: Schematic of the requirements derivation process. Includes a representative sample of the specification of subject matter expert's SoK from Decision Ladder States. Each SoK resulted in at least one CWR and IRR set.

what the priorities should be given the time and resource constraints of the dissertation process. Prioritization came from a combination of 1) assessing the relative importance of the requirements to the domain itself and 2) that a feasible pathway to prototype solutions existed. This is particularly true for the critical link requirements identified in the figure. These two requirements collectively contribute to the overall Timeline Margin calculation which imposes the 'highest-level' constraint that exists during EVA operations. How we go about addressing each of these requirements are through the prototype DSS solutions discussed in the next chapter.

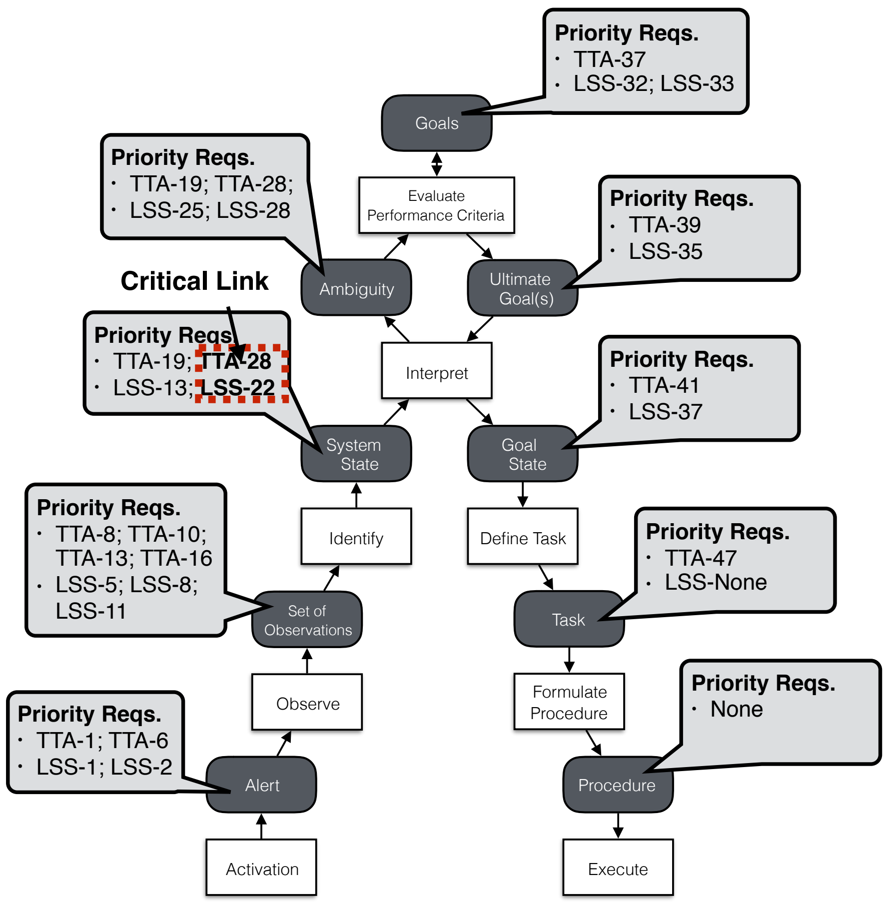



Figure 3.20: Prioritized requirements for initial DSS prototype development. Starting in the bottom left, the DL provides a sequenced set of stages which map to operators within the domain. At each stage, the prioritized requirement IDs are shown. Refer to Appendix A.2 for the full list of requirements.

The DL itself helped me start to allocate what I thought would be needed to even attempt addressing the prioritized requirements. E.g. What alerting features will I include in a simulation environment? What specific observations do I want my subjects to be dealing with and what system states do I want them to assess. The resulting goal states, tasks and procedures lend themselves to thinking more directly about how that envisioned work environment will actually look like. This was in part where the two DSS prototype designs came from. One that reflected the process of traversing the DL (in with current tools) and then one that re-imagined how that same process might take place with new tools. The requirements I derived and ultimately prioritized helped fabricate this effort. Additionally, this train of thought lead me to consider the importance of not just the system design, but the shape of the context in which it would be used and thus would need to be created to evaluated it appropriately.

### 3.3.3 ConTA DSS Design Implications

In summary, the activity template mapped EVA work functions to the various operational phases to refine our understanding and work models for potential avenues for study. Life support system monitoring and timeline tracking/alteration in particular spanned across all relevant EVA operational phases. The decision ladder depicted in the following section provides further insight into the processes involved in life support system monitoring and provides the basis to link those processes to DSS design requirements.

As with any design process, design solutions stem from design requirements. Therefore, the SME knowledge captured from the decision ladders were each extended to a set of CWR and IRR statements to begin that design process. (See Appendix for full documentation)

The CWRs convey a set of functional DSS requirements for the envisioned world of EVA execution, specifically related to life support system monitoring. They capture "what the [EVA flight controller] operator was thinking Elm et al. (2003, p. 376)" during EVA execution to reflect the cognitive activity required to achieve the overall goal of life support system monitoring. For example, the DSS should handle the alerting processes of assessing state variables throughout the various operational phases and consumable levels in comparison to expected or historical values, in the forms of trending as well as in absolute terms of critical upper and lower bounds. Furthermore, the DSS should also have the capability to recognize the current state of the life support system as it relates to the geospatial and temporal location of the EV crew members established by the timeline. For system state estimation, the DSS should track the completed and remaining EVA task priorities and estimate the affordances that the life support system can provide in the presence of timeline alterations. Both life support margins (i.e., relative to the critical limits of consumables/system variables) and timeline task margins (i.e., relative to previously performed or accepted time limits) should also be estimated according to EVA progression for timeline forecasting. Finally, the DSS should estimate the appropriate distribution of task-relevant assets, such as tools, crew, and hardware, for current or altered timeline projections.

The IRRs convey the set of information relations required to perform the activities conveyed at the cognitive work level to establish meaningful context (Elm et al., 2003). For example, the DSS should calculate the deviations of consumables data with respect to a priori expected values. Simply tracking the current life support system values independently does not yield operationally relevant information. Additionally, the DSS should estimate a measure of geospatial accessibility to regions such as worksites or storage depots. The carrying capacity of the life support system variables should also be incorporated into the timeline-tracking activities to link the potential affordances to potential timeline alterations.

While providing official 'proof' that the aforementioned process meets the intended goals of formally synchronizing the CSE and SE requirements derivation process is beyond the scope of a single article, we can argue the following reasons why this process is helpful: (a) It delivers DSS requirements at an appropriate level of abstraction to convey the cognitive purposes/goals with expressed relations to the raw data required by the work domain; (b) it explicitly considers the work inherent to the work domain from a joint

Table 3.5: Assessment of Cognitive Systems Engineering-Inspired Requirements Characteristics Versus Traditional Systems Engineering Requirements Characteristics (Turk, 2006); S=Somewhat.

| Requirements Characteristics | Achieved? |
|---|---|
| Necessary | ✓ |
| Correct | ✓ |
| Unambiguous | ✓ |
| Prioritisable | ✓ |
| Traceable | ✓ |
| Results oriented | ✓ |
| Quantifiable, measureable, and verifiable | S |
| Feasible, attainable, and achievable | S |

human-systems integration perspective; and (c) the process is traceable and tractable. As opposed to the FAN model, where the linkages expand organically in an ill-defined manner, we demonstrate the structured and repeatable application of decision ladders to analyze specific work functions identified in the WDA, which remains tractable. Additional requirements, such as representation design requirements and presentation design concepts, can be readily incorporated and associated to their parent CWR and IRR statements in the detailed requirements definition and design phases. In the event that requirement additions or modifications are warranted, the SoK statements provide suitable anchor points to incorporate updates to the set of requirements.

Table 3.5 shows an assessment of the derived CWR/IRR statements in regard to the characteristics of traditional SE requirements. The stated requirements meet the characteristics of being necessary, correct, and unambiguous because they were explicitly derived from SME knowledge of the work domain. Articulating requirements from each SME SoK enables the resultant requirements to be weighted and prioritized against one another, in addition to being traceable to their source CSE model elements. The CSE practitioner plays a key role in the translation of SoK statements to formal requirement statements. Ambiguity in requirements is minimized by iteratively critiquing the requirements statements with domain experts. Finally, the requirements are considered results oriented because the requirements are linked to the intended support of DSS design. Two characteristics, at this early point in the SE design process, are open to further assessment. Because we have neither translated the requirements into a representational prototype nor tested a prototype in a relevant operational environment, we cannot currently comment on the qualities of feasibility or measurability. Finally, the insights gained from this work were formally recognized by the EVA management community as a valuable contribution to the early functional requirements derivation process currently being conducted.[2] Prior to this research, the set of SE requirements for future EVA operations emphasized the physical/hardware-related components of the EV spacesuit and lacked a more comprehensive perspective of EVA work domain elements identified in this study. Particularly, we successfully articulated to the SE practitioners the utility and importance of considering the IV operator work and the development efforts and considerations that will need to be included in the overall EVA systems development process.

### 3.4 Insights drawn from CWA

The potential avenues for DSS development efforts within the EVA work domain are vast, as indicated by the 13 generalized functions identified in Figure 3.10. Construction of the CWA models incrementally revealed the constraints pertinent to EVA operations. First, the WDA identified the goals and constraints present within the EVA domain, independent or a particular mission or location. The WDA grounded the development efforts of the ConTA and was valuable in structuring and prioritizing what envisioned purposes were appropriate to pursue for DSS development. In this study, the general functions of life support system and timeline management were prioritized for the application of the control task analysis. The ConTA elicited details related to the cognitive demands imposed on EVA domain operators and provided a mapping of activities to phases of operation as well as a starting point for requirements definition. The culmination of these modeling efforts helped to reveal some underlying inconsistencies between the current work domain and a

[2](for news coverage of the 2016 NASA@Work Mars EVA Gap Challenge, see http://www.nasa.gov/feature/nasawork-february- 2016-monthly-winners).

future context. In particular, the functions of providing adequate life support system and timeline management provided by MCC becomes impaired when real-time communication amongst the EVA operators is severed. The decision ladders and requirements derived in this Chapter convey the wealth of considerations that must be taken into account if these functions are to be adequately supported.

It can be overwhelming to consider the volume and variety of work performed to support EVA operations. What the CWA provides is a structured tool to orient practitioners while capturing the context of EVA operations to go deeper in our understanding of the domain The SoKs specified in the ConTA convey the breadth of considerations that can have implications for EVA execution. The research began without any preconceived notions of what support systems might be needed for EVA operations. After completed the first two phases of CWA, I arrived at two key work functions with some high level design requirements in hand worth carrying into prototype development.

When addressing the requirements, there are three approached: 1) to fully apply the specification as a need, 2) partially accommodate its intent, or 3) omit it all together. The extent to which the DSS satisfy these demands is an open area of design hypothesis. The requirements only specify that CWR and IRR exists in the domain and must be addressed in some way.

This work heavily leverages a top down WDA perspective to guide development - the lower level AH levels are so ill-defined given the future technology development likely. Thus the top-down perspective is amenable to research for envisioned worlds. This work emphases starting at the upper levels of AH to tease out CWR and IRR that will then lead to subsequent physical elements in the domain. Establishing this purpose brings resolution to the envisioned world to help make it reality.

The ultimate goal within the CSE community is to bridge the gap between analysis (cognitive or otherwise) and useful DSS design. The process demonstrated in the article provides a tractable way to reason about the requirements of the DSS design. The design process is an iterative process, and its success depends on a deep understanding of the specifics of the user's work (Deans and Hoffman, 2010a). In particular, for envisioned systems, the nature of the user's work will become more available the further along in the design process a practitioner progresses until the envisioned world becomes reality. First establishing the cognitive work and required information relationships is paramount before one can hypothesize the representational artifacts of DSS design. By decomposing the requirements definition process, we can more readily accommodate the iterative representation design process while maintaining linkage to the fundamental elements inherent to the work domain under investigation, which remains a needed area of future research (Lintern, 2005; Read et al., 2015).

## 3.5 Summary

In this chapter, requirements of a DSS for use in the EVA work domain was derived from CWA. We implemented an incremental analysis process that first established the EVA work domain and the associated elements, using an information flow model and AHs as part of the initial WDA. Second, we refined our EVA work domain understanding by delineating the operational phases and their associated work functions via a ConTA. This process enabled the scoping of the design process to focus on particular aspects of the domain that warranted support. Finally, we leveraged a decision ladder to convey and map SME SoKs associated with EVA life support system monitoring to a structured requirements format for DSS development. Specifically, at each analysis phase, the various CWA models were used to guide analysis efforts to arrive at a set of cognitive work and IRRs for DSS development. Figure 3.21 summarizes these steps that feed into the remaining chapters of this thesis.

The CWA framework provided a useful, systematic, tractable pathway to derive purposes and goals that an EVA DSS should strive to manage in the envisioned work domain. In addition, DSS requirements were purposefully framed to be compatible with the traditional SE requirements definition currently underway within the NASA EVA engineering

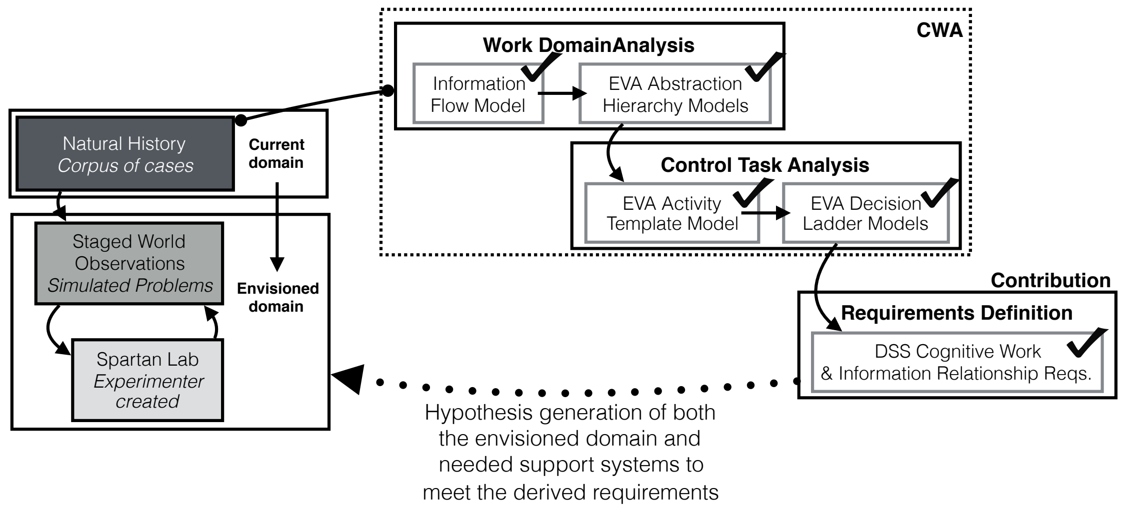



Figure 3.21: Transitioning from CWA modeling and requirements definition to ecological and DSS design considerations.

community. Future work aims to extend the stated requirements into representational design requirements for DSS prototype development as well as human-in-the-loop testing of the DSS prototype situated within the envisioned work domain. At this point in the process, perspectives from the envisioned world problem as well as the contextual design process provide useful considerations to help fabricate and test these hypothesized prototypes in an envisioned work domain.

# CHAPTER 4

# EVA DSS PROTOTYPE DEVELOPMENT

The following Chapter links the requirements development effort described in Chapter 3 to the resultant DSS prototypes. Before explaining the prototype designs, a few considerations are worth noting: 1) Requirements do not provide design solutions. Solutions are simply hypotheses of how those requirements might be satisfied. 2) When designing any technology, the requirements help specify what capabilities the system should strive to provide, but the requirements do not always provide the necessary environmental/operational context within which those capabilities will be used. 3) Requirements do not always specify the necessary features of the (envisioned) work place setting. It is this collective effort to both satisfy the requirements identified and define (and construct) the envisioned work domain that is required for meaningful DSS development. It is important to consider the operational use-case of the design at the outset to verify those designs, do in fact, support the intended requirements. This chapter aims to describe how I approached this dual effort.

As the previous chapter revealed, the IV operator is an ideal user of DSS technology based on the likely pivotal role they will play in future missions. In addition, work functions the IV will likely need to manage in a future setting were identified and prioritized when the design requirements were created. This evolutionary process was necessary to begin the translation process from how things are done today to how they might be done in the future. Explicitly showing the shifts of work domain characteristics (constraints) is the role of the CSE practitioner - as most others will not have the broad understanding that the requirements derivation process afforded. The CSE practitioner should seek to unify any useful opinions by SMEs and other subsystem designers and unite them under a common framework. Chapter 4 and 5 outline these shifts by demonstrating the hypothesis process regarding both potential DSS and envisioned user environment designs.

As part of this process, DSS prototypes were constructed to demonstrate the translation process and how that process can manifest in the form of two distinct DSS configurations: a Baseline DSS and an Advanced DSS. Both systems provide the underlying support for the work functions of Timeline Tracking and Alteration (TTA) and Life Support System (LSS) Monitoring, but implement different design features. In effect, the work demands remain the same between the two configurations while the process by which the work is performed by the user is different. The Baseline DSS was based on present-day technologies currently used by the EVA flight controller community. The Advanced DSS involved the design of new software technology to support the envisioned future work. Subsequently, the Advanced tool also incorporates considerations of new training and mental demands that will likely exist in a future operational setting. As this chapter and subsequent chapters show, the Baseline configuration is serviceable and is similar to the methods currently used. However, the Advanced DSS is not only more proficient, it is more readily extensible to tackle the avalanche of additional support needs already identified by the full requirements documentation.

As specified in the contextual design literature (Beyer and Holtzblatt, 1998), the design process itself should shift focus from a specific system under consideration to the work of potential users. As a result, the system design will result from the agreements between all relevant people involved in the domain. And in order to obtain those agreements, the relevant people must be speaking the same language. The inception of the envisioned domain requires a careful consideration of the assumptions that establish and frame the domain. In effect a vision for what the future might entail must be articulated. At this stage in the design process, this brief scenario coupled with articulated prototype design hypotheses begins this envisioning process, with the intent that it will be expanded upon in future iterations. Furthermore, the development of two different prototype artifacts provides a mechanism to synthesizing a common vision.

The following two sections delineate each component of the DSS prototypes. Additionally, a walk-through description of the simulation environments is provided of the envisioned work domain for which each respective DSS is hypothesized to support. These descriptive efforts contribute to the overall envisioned world development efforts. The need to clearly state the assumptions considered (and dismissed) so that a similar reference point can be made for future technology development efforts is key. Regardless of the hypothesized work demands of a future environment, existing work domain demands must also be considered. Table 4.1 shows the resultant development timeline for both DSS prototypes and their respective testing environments. The remainder of this chapter describes the prototype designs and how they fulfill the requirements established in Chapter 3. Chapter 5 describes the simulation environment development and human-in-the-loop experimental design. Chapter 6 discusses the results from the evaluation of the DSS prototypes.

## 4.1 Brief Scenario Description

Up to this point, the EVA work domain has been examined to undercover the various goals, constraints, and work functions that exist within it. But the motivation for acquiring this knowledge is not to design a DSS for the current EVA work domain. Instead, this work aims to support future EVA operations that have yet to be designed. So in order to better understand the DSS prototype designs described in this section, a realistic depiction of future operations is needed. A full description of the scenario development efforts is discussed in Chapter 5. The remainder of this section defines the scenario and defines some basic assumptions used to place the resultant DSS prototypes in the likely future.

Scenarios are a useful tool to begin the envisioning process to establish concrete context. These stories help describe the setting, actors, systems wrapped in a plot describing human activity, see Carroll (2000, Ch. 3) for more details. Figure 4.1 shows the scenario derived and implemented for this thesis. In this EVA scenario, the number of in-flight crew members are limited to three (2 Extravehicular (EV) crew and 1 Intravehicular (IV) crew) who are located in deep-space at a potential variety of destinations such as asteroids, Mars

Table 4.1: Prototype and environment development process.

| Legend: ~ Initial dev. ○ Coding ✔ Testing | | | Baseline DSS: Prototype Development | Baseline DSS: Environment Design | Advanced DSS: Prototype Development | Advanced DSS: Environment Design |
|---|---|---|---|---|---|---|
| 2014 | Summer | | Cognitive Work Analysis Modeling | | | |
| 2014 | Fall | | | | | |
| 2015 | Spring | | | | | |
| 2015 | Summer | | | | | |
| 2015 | Fall | Sept | ~ | ~ | ~ | |
| | | Oct | ~ | ~ | ~ | |
| | | Nov | ~ | ~ | ~ | |
| | | Dec | ~ | ~ | ~ | |
| 2016 | Spring | Jan | ○ | ~ | ~ | |
| | | Feb | ○ | Pilot Testing | ~ | |
| | | Mar | ○ | | ~ | |
| | | Apr | | | ○ | |
| | Summer | May | | | ○ | ~ |
| | | Jun^ | | | ○ | ~ |
| | | Jul | | | ○ | ~ |
| | | Aug | | | ○ | ~ |
| | Fall | Sept | | | ○ | ~ |
| | | Oct | ✔ | | ○ | ~ |
| | | Nov^ | ✔ | | ○ | Pilot Testing |
| | | Dec | ✔ | | ○ | ~ |
| 2017 | Spring | Jan | | | ○ | ~ |
| | | Feb | | | ○ | ~ |
| | | Mar | ✔ | | ✔ | |
| | | Apr | ✔ | | ✔ | |
| | Summer | May | Human-in-the-loop testing data post-processing | | | |
| | | Jun | | | | |
| | | Jul | | | | |
| | | Aug | | | | |

^ supporting NASA Analog - BASALT deployment

or the moons of Mars. The exact location is not important. Rather, the defining criteria in this scenario is the inclusion of time-delayed communication between the crew and Earth. Regardless of the EVA objectives or particular deep-space destination, the characteristics of the EVA work domain discussed in Chapter 3 will need to be supported. The DSS prototype design efforts are focused to support the IV crew member. Of particular interest is how to support the IV operator performing the work functions of life support system and timeline management in addition to facilitating the communication flow amongst the larger flight team.

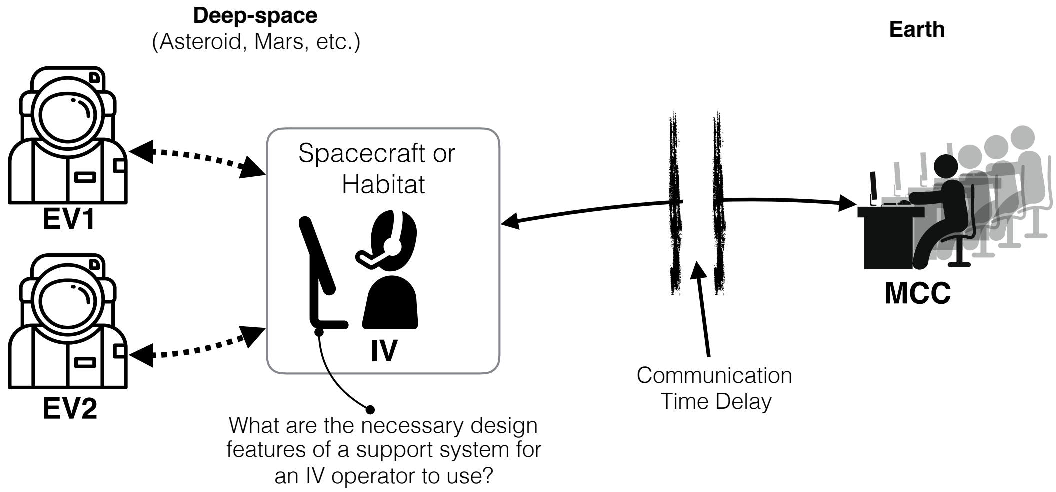



Figure 4.1: Abstract depiction of an envisioned EVA operational environment.

Key assumptions surrounding the EVA scenario shown in Figure 4.11 include:

- The crew are performing a planned EVA with all necessary preparation and products already developed. This scenario assumes the EV crew have successfully exited the vehicle and EVA execution is underway.
- Future crews will likely have limited preparation time and familiarity with the particulars of any given EVA timeline. As the total number and frequency of EVA increases, the preparation time for each EVA will decrease.
- While the EV/IV crew will be highly trained to perform future EVA, they may forget details that could lead to improper task execution.
- Similarly, the crew may misremember or simply execute tasks incorrectly which could also result in tasks being improperly performed.
- The IV is viewed here as the first line of defense in ensuring task execution verification (e.g. ensuring successful completion of tasks to specifications, identifying and/or resolving incorrectly executed tasks, etc.) In effect, the IV operator is responsible for ensuring the crew are doing what they need to be doing, per the specifications in the EVA timeline.
- The EV crew will undoubtedly have more technologically advanced spacesuits in future operators. This scenario does not include any technologies beyond what is present in the current ISS spacesuit.

- MCC will likely shift to a mission support role instead of command role under time delayed operations, particularly for tactical operations (e.g. dynamics that occur more quickly than the round-trip communication time-delay). Therefore, enabling the crew to have more tactical decision-making capability becomes a key consideration to support.

The dimensions of complexity in this scenario are vast, but that is why the CWA was performed. Not all constraints have equal impact on the work domain or can even be realistically addressed at this stage of design. The prioritized requirements derived in Chapter 3 provide a valuable starting point to promote how future crews might successfully conduct future operations. The CWA identified 12 work functions performed during EVA execution, each of which could be an entire area of design focus. But because the requirements were derived and prioritized based on the constraints that shape EVA execution, the DSS prototype development process could start with consideration of a 'minimum set' of design constraints. Subsequently, this work focuses on supporting two primary work functions that have overarching implications for EVA operations: TTA and LSS. Future crew will always need to know life support capacity and remaining timeline demands, and it is imperative to support these work functions throughout EVA execution. The prototype development efforts are dedicated to exploring how those work functions and their associated requirements could be satisfied in a realistic work environment throughout the remainder of this chapter.

## 4.2 Baseline DSS Development

Given the limited formal examination of the EVA work domain as well the complexity of the domain itself, the realities of how the domain functions presently can be difficult to convey to a general audience (hence the CWA). However, the specific work artifacts and tools utilized today provide a common starting point for prototype develop, as discussed in Chapter 3. Therefore, the Baseline DSS mimics present-day support capabilities to help illustrate the departures that will likely occur from present-day tools and operations. In other words, the Baseline DSS is a prototype that implements the state of technological capabilities currently in use to examine how that design fares in an envisioned future work environment.

The Baseline DSS is comprised of three main focus areas: life support system displays, timeline artifacts, and communication systems. Figure 4.2 shows each prototype component in the form of their respective Focus Areas which are described in the subsequent sections. Additionally, each focus area is identified based on the specific requirements they aim to satisfy. The defining characteristic of the Baseline DSS is the extensive use of the IV operator to meet the specifications of the bulk of requirements.

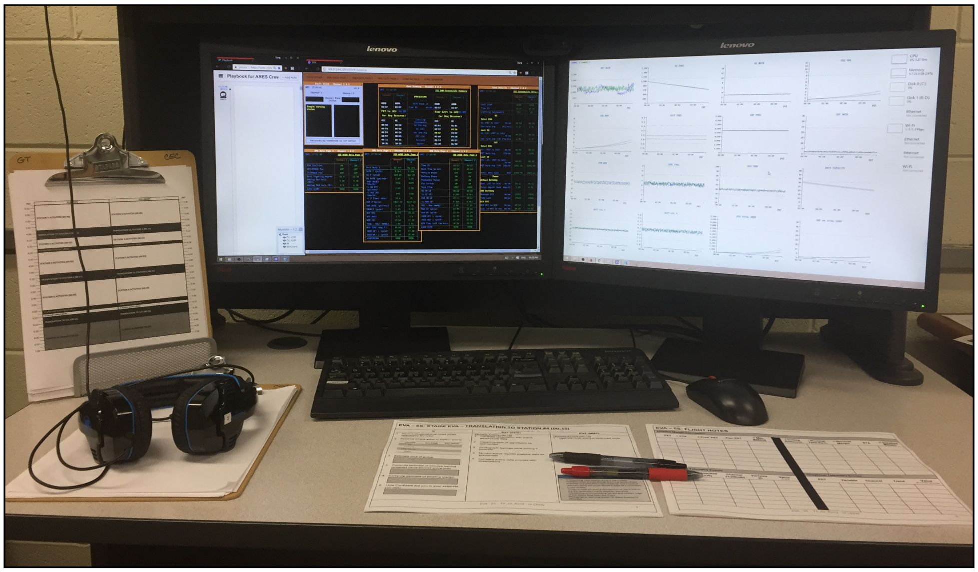
Throughout the remainder of this section, each focus area of the Baseline DSS design is described and linked to the design requirements. An integrated scenario description of an envisioned future EVA work domain is also provided to describe the expected work demands and how the Baseline DSS provides support. It is through this narrative and the subsequent simulation study (Chapter5) that the existing domain tools can be evaluated in an envisioned context.

### 4.2.1 Focus Area Descriptions

*EVA Life Support System Displays*

The life support system (LSS) focus area is divided into two digital display types: 1) numerical displays and 2) graphical displays. The data included on these displays come from the telemetry streamed from the EV crew spacesuits. In total, approximately 60 variables per spacesuit are included in the displays (Figures 4.3 and 4.5), with some duplication of variables between the two. The interface formatting (e.g. fonts, colors, icons, etc.) for the LSS displays mimic present-day flight controller console displays.

The numerical display, as shown in Figure 4.3, arranges the data into spacesuit subsystem and consumable detail windows based on the current ISS spacesuit telemetry. Channel 1 and 2 represent EV 1 and EV 2, respectively into two columns within each window. Ad-



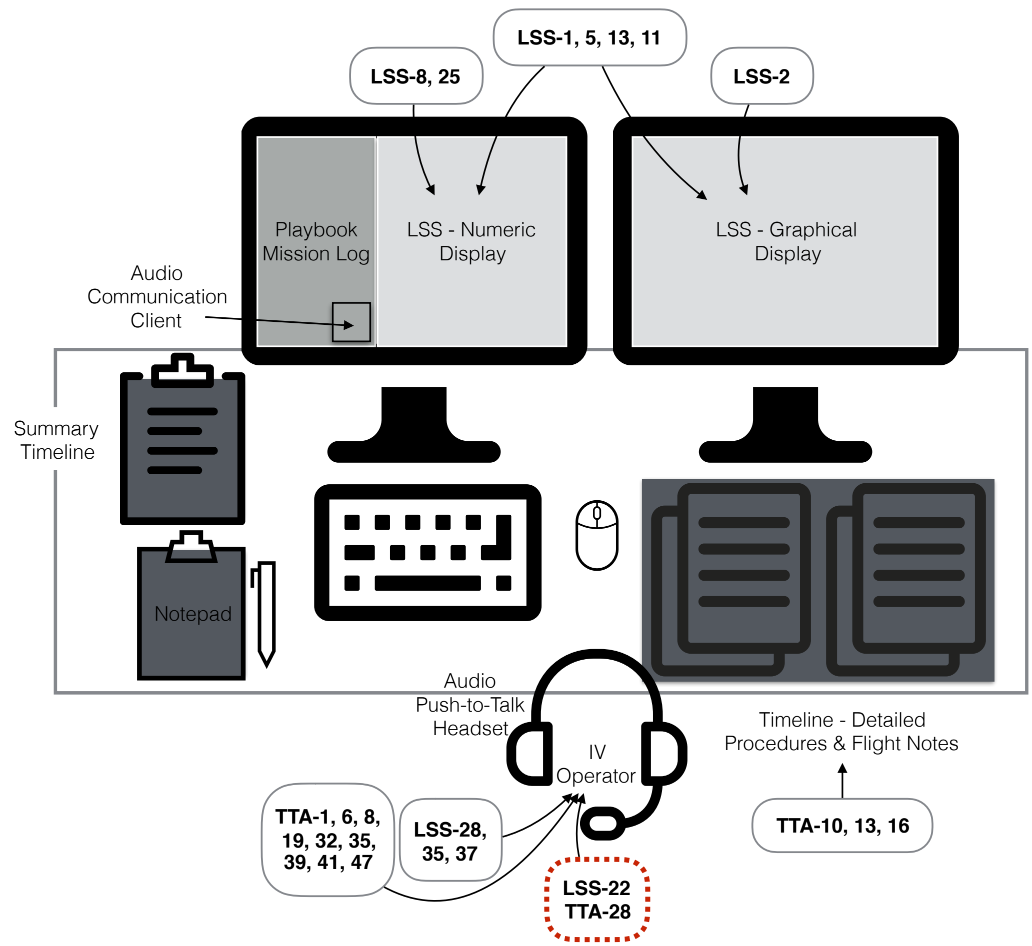



Figure 4.2: Baseline DSS prototype (Top) with component descriptions (Bottom). Requirement IDs are specified and organized by focus area.

ditionally, a Fault Stack window shows printed warning messages that are generated from the caution and warning system. Each unique telemetry variable name is shown in purple and their respective values are shown in green. All value formats are Hours:Minutes unless units are otherwise specified. Some key details to note in these displays is LAST SCAN, Time EV, and the consumables summary window (shown in Figure 4.4).

The LAST SCAN variable indicates whether or not a stable connection exists between the console displays and the spacesuit systems: *GOOD* signifies a stable connection and *BAD* indicates a communication dropout. In the event of a *BAD* connection, the entire column of data values turns from green to yellow to signify stale data. Once a stable connection is reacquired, the data turns back to green to indicate a good connection. For any green variable that exceeds a programmed limit, the variable turns red to indicate a violation. The Time EV variable corresponds to the EVA phased elapsed time (PET) which signifies how long the EVA has been in the execution phase. Currently, the official start of EVA is when the spacesuit is disconnected from the ISS life support systems and is operating on its own power and life support systems.

A close-up view of the consumables summary window is shown in Figure 4.4. Six limiting consumable variables are tracked in present-day operations:

- **O2 EVA Avg:** Oxygen estimate that incorporates an averaged calculation over the entire duration of the EVA from start to current point. Think of this as a cumulative average estimate of remaining oxygen throughout the EVA.
- **O2 (10):** Oxygen estimate that incorporates an averaged calculation over the last 10 data passes. Think of this as a more localized moving average estimate of remaining oxygen.
- **CCC EVA Avg:** 'contaminate control cartridge' is an estimate of how much scrubbing capability the spacesuit has to remove carbon dioxide averaged over the entire duration of the EVA from start to current point. Think of this as a cumulative average estimate of remaining carbon dioxide scrubbing capability throughout EVA.
- **CCC (10):** carbon dioxide scrubbing capability estimate averaged over the last 10 data passes. Think of this as a more localized moving average estimate of carbon dioxide scrubbing capability.


Figure 4.3: LSS - numerical console display

- **Battery:** An estimate of how much battery amperage is available to support spacesuit subsystem operations.
- **Water:** An estimate of how much water is available to support spacesuit subsystem operations.

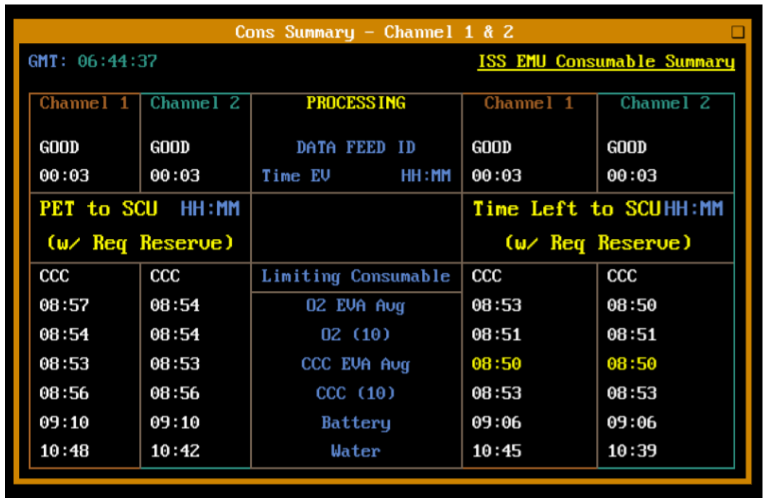



Figure 4.4: LSS - numerical console - consumables summary display.

Any one of these consumable variables can impose an overall limiting constraint on the time available to perform an EVA. The most limiting consumable for each and between crew members can fluctuate throughout the execution of an EVA. The most limiting consumable is shown in yellow for each crew member throughout the EVA. As shown in Figure 4.4, Time EV reads *00:03* to signify the EVA has been in execution for 3 minutes and the currently limiting consumable is CCC EVA Avg *08:50* which means the spacesuit in this case for both crew members can support 8 hours and 50 minutes of operations at this instance in execution. All variables are currently estimated based on sensor data and measurements made before and during the EVA in conjunction with estimated usage-rates to calculate a projected estimate of time remaining.

In addition to numeric raw sensor data and time estimates of EVA telemetry variables, a subset of the data (16 variables for each EV crew) is also shown in graphical form as shown in Figure 4.5. The y-axis for each graph scales to their respective variable value and the each x-axis shows the EVA PET time and increases as the execution progresses.

The red horizontal lines represent upper and/or lower engineering limits. EV1 and EV2 telemetry values correspond to Channel 1 and 2, respectively. Each graph shown in Figure 4.5 conveys an example of approximately 5 hours PET that is representative of the trends found during of EVA operations. EVA telemetry can present in multiple trends formats including variables that increase and/or decrease, have various levels of sensor noise, are linear and/or exponential. Not only do the trend variables exhibit global trends, they also can exhibit local deviations such as step changes or slope changes as shown in the variables O2 Rate, SOP Pres, and BATT LVL V. The Baseline DSS has a data refresh rate of one data pass every 20 seconds. In present-day operations, telemetry data shares bandwidth constraints with biomedical data and receives approximately 30 seconds of data every 2 minutes.

The LSS displays have limited interactive capability. The numeric windows can be rearranged and the zoom can be controlled to adjust the font sizes. Otherwise, the displays are meant to be observed and monitored during EVA execution much like how flight controllers currently observe the variety of data during ISS EVA operations. Color changes signify alerting events in the numeric display, and red line limits signify operational/engineering limits in the graphical display. The numeric display in particular incorporates numerous redundant variables across each window. In total, the LSS console displays represent a key portion of the present state-of-the-art in spacesuit telemetry monitoring. While other auxiliary console displays are leveraged during EVA operations, the aforementioned displays represent the core data acquisition system used for spacesuit telemetry (Luta, 2010, 2011a,b).

The current Baseline DSS life support system design directly supports a portion of lower level alerting and sets of observations as specified in the LSS decision ladder. In total, the numeric and graphical displays provide entry level support to meet approximately seven of the eleven prioritized requirements. To meet the remaining LSS requirements, the IV operator must manually generate the necessary system states and address the ambi-

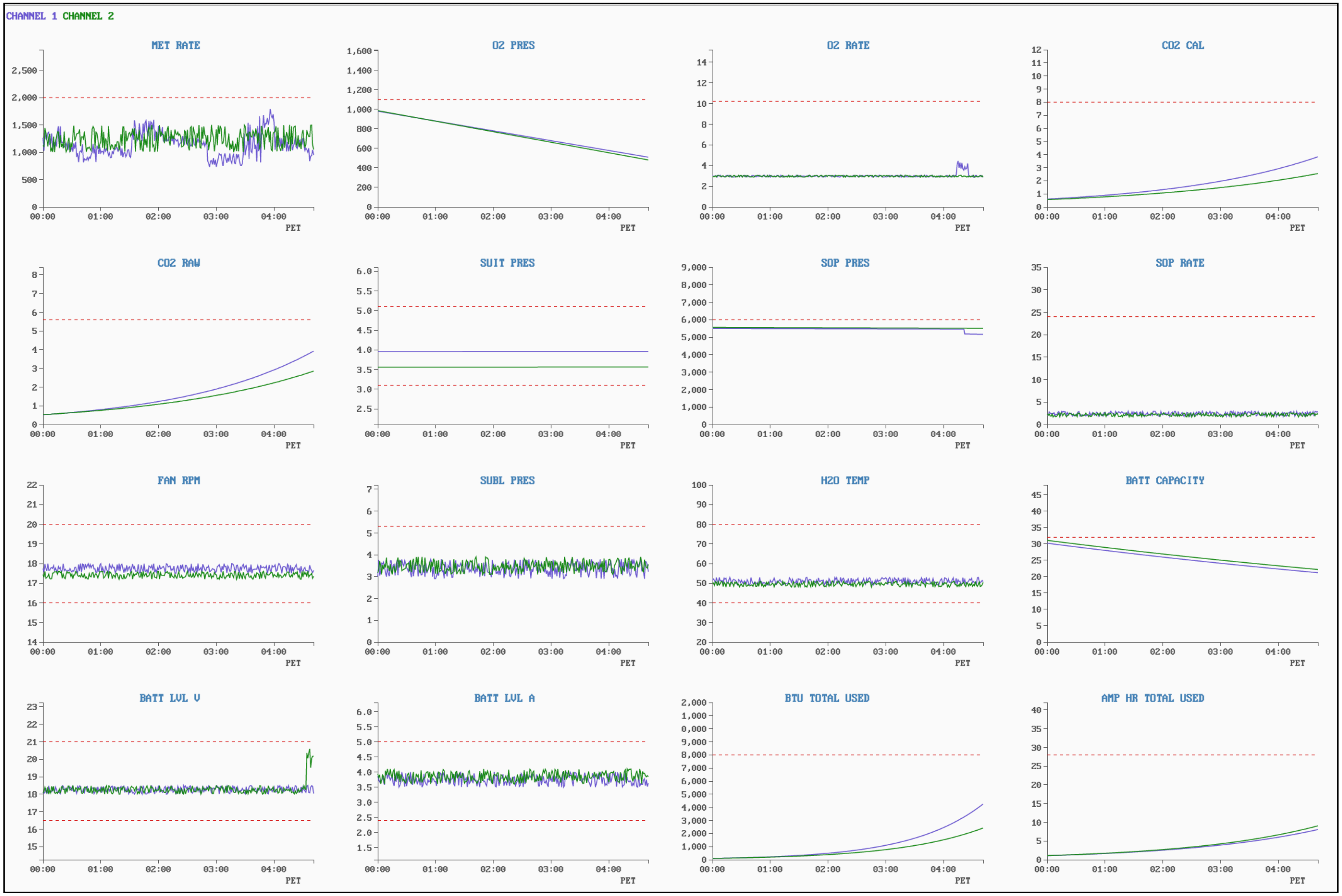



Figure 4.5: LSS - graphical console display

guities without any technological support. As indicated by the red-dotted border, a critical component left for the IV operator to integrate is the relationship between timeline progress and life support system capacities.

*EVA Timeline Artifacts*

As discussed in Chapter 3, EVA timelines contain a variety of content that typically require months to years to develop. The overall intent of a timeline is to convey as much detail as necessary to ensure all task objectives are completed safely and to maintain coordination amongst the entire flight team. The Baseline DSS incorporated the similar content and detail exhibited in present-day operations timeline artifacts. As a result, all timeline products in the Baseline DSS were static, paper-based artifacts that maintain the structural format of ISS EVA operations. Additionally, Apollo EVA and NASA Analog timeline content and objectives were incorporated into the Baseline DSS timelines to add flight relevant objectives pertinent to planetary exploration objectives. Future operations are envisioned to contain more exploratory tasks which represents a departure from the engineering tasks primarily performed during ISS EVA operations. Figures 4.6 and 4.8 show the resultant Baseline DSS summary and detailed procedure timeline products, respectively.

The summary timeline shown in Figure 4.6 conveys the sequence of activities to be performed for the entire period of the EVA. The summary timeline is intended to provide the highest level EVA summary of activities to be completed and when. The summary timeline developed for the Baseline DSS was modeled after the 7-hour PET EVAs demonstrated during Apollo 17, which had the crew perform overhead activities to start and end the EVA with periods of translation and station activities throughout execution (Miller et al., 2017a). The EV1 and EV2 timelines are shown side-by-side to provide overviews of when each crew member is scheduled to perform particular activities. In this case, the two EV crew perform each activity group in-sync with each other. However, as shown in the detailed procedures in Figure 4.8, each EV crew performed different tasks within each activity

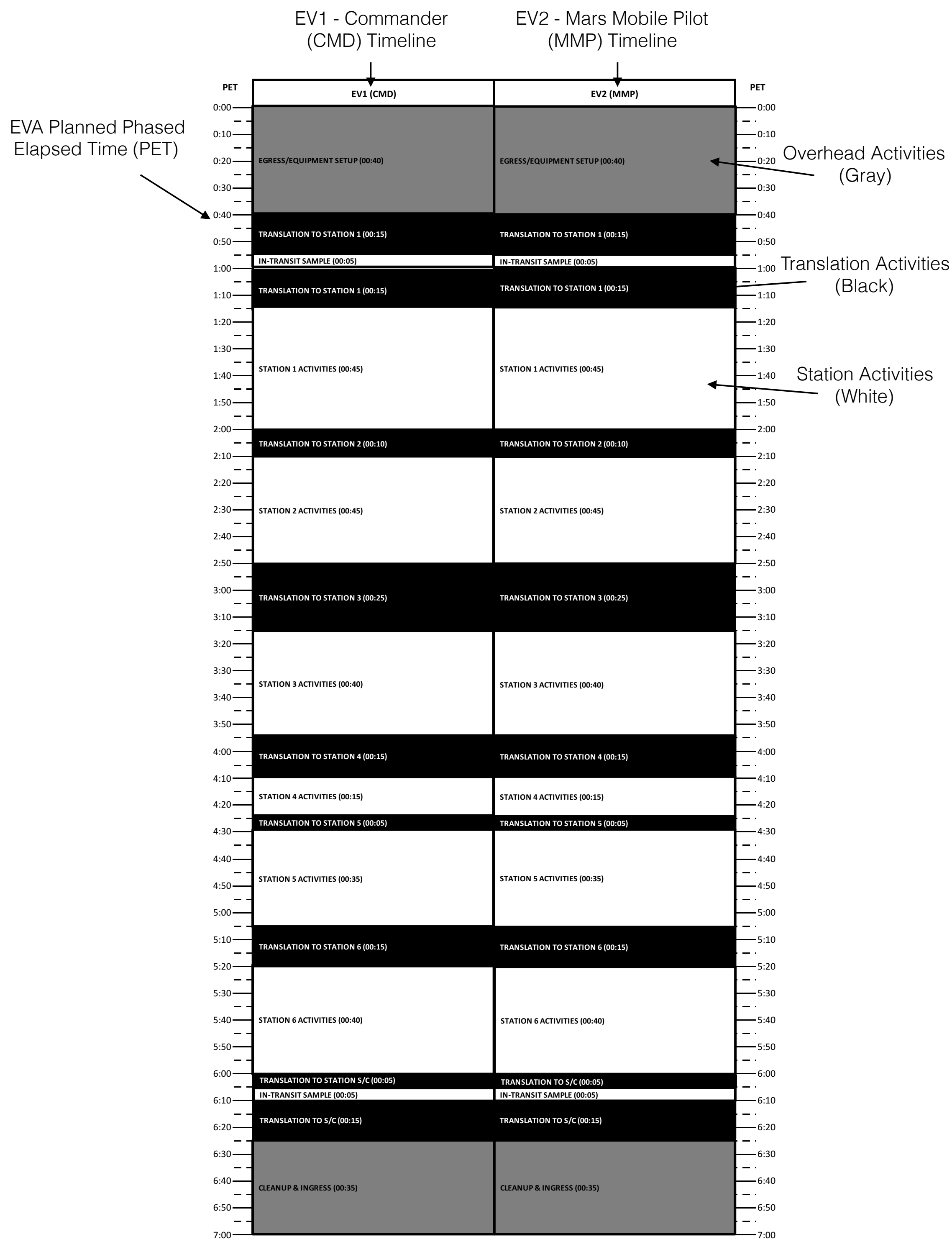



Figure 4.6: Baseline DSS summary timeline.

group.

The detailed procedures for each member of the flight team are shown in Figure 4.8.

The detailed procedures document provides all necessary details required to achieve each EVA objective. The document is divided into three columns that correspond to each EVA flight team member [IV (LEFT), EV1 (Middle), EV2 (Right)]. In the Baseline DSS, an IV operator performs the stated tasks in the far-left column, while the EV crew perform their respective columns of actions. All primary tasks are underlined, all sub-tasks are numbered, and all procedures are indicated with checkboxes. Time duration estimates are provided where appropriate in the form of (Hours:Minutes) next to their respective task or subtask description. Additional features of the timeline include action boxes (in gray) to be filled out by the IV operator. Notes, Cautions, and Warning messages are inserted where appropriate throughout the document for reference.

To assist with the expected tasks of the IV operator, a Flight Notes calculation sheet was provided. This sheet is shown in Figure 4.7 and supports three main categories of action: 1) minutes behind and timeline margin calculations, 2) recording numerical telemetry events, and 3) recording graphical telemetry events. The content of these specific actions is explained below in the walk-through scenario description. In general, these calculation and recording responsibilities are representative of the actions to be expected by an IV operator in an envisioned EVA context. While such a structured sheet does not exist in reality, it reflects the *ad hoc* calculations performed by the EVA flight controls in MCC now.

In total, the timeline products incorporated three paper artifacts to support timeline management. These materials assume a desired EVA timeline exists and their content remains static once defined throughout EVA execution. However hand-written annotations are allowed (and expected) to alter the materials as needed throughout execution. A summary view provided an overview of the EVA timeline activities and the detailed procedures provided the full set of expected tasks, subtasks, procedures to be performed during the EVA. A structured flight notes rubric was included to assist with hand calculations and event recording to be performed throughout EVA execution. The summary and detailed procedure views maintain the same form and structure as present-day ISS EVAs and the

**EVA – 6S: FLIGHT NOTES**

**Timeline Margin Calculation**

| PET | + ETA | = Pred. PET | - Plan PET | = <u>Min. Behind</u> |
|---|---|---|---|---|
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |

| Limiting Resource | - Nominal Time Rem. | = Nominal Margin | - ETA | = <u>Timeline Margin</u> |
|---|---|---|---|---|
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |

**Numerical Telemetry Events**

| PET | Yellow/Red (Y/R) | Channel (1/2/Both) | Variable ID (if red) | Value (if red) |
|---|---|---|---|---|
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |

**Graphical Telemetry Events**

| PET | Variable | Channel | Trend | Value (if exceed bounds) |
|---|---|---|---|---|
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |

EVA - 6S - TX_S1_PRAC - IV CREW 8

Figure 4.7: Baseline DSS timeline flight notes.

## EVA – 6S: STAGE EVA – TRANSLATION TO STATION #4 (00:15)

### IV

1. Record Observational notes *when directed* by EV crew
2. Systems Check **prior** to station arrival

| Variable | EV1 (CDR) | EV2 (MMP) |
|---|---|---|
| O2 | | |
| Pressure | | |
| EMU Faults | | |
| Water | | |

2. Estimate time of arrival
3. Compute estimate of minutes behind (projected minus planned arrival time)
4. Compute estimate of timeline margin
5. How Confident are you in your estimate (+/- min)

### EV1 (CDR)

TRANSLATION (00:15)

1. Correlate observation with active geophysical data
2. Inspect targets of opportunity as appropriate
3. Photograph features while driving if possible
4. Monitor active regolith analysis data as appropriate
5. Correlate active data sources with observations

### EV2 (MMP)

TRANSLATION (00:15)

1. Operate rover along preplanned route

**NOTE**

- In traversing from Station #3 to 4 the surface characteristics should change from the blocky Front material to a smoother mare material. The Traverse will pass along the south western edge of a secondary crater cluster.
- Things to look for during this portion of the traverse are the secondary crater deposits and their relationship to surrounding terrain and eastern edge of the debris flow from the Front.
- Photographic documentation of these features is desirable.

EVA - 6S - TX_S1_PRAC - IV CREW 1

## EVA – 6S: STAGE EVA – STATION #4 ACTIVITIES (00:15)

### IV

1. Record PET at Arrival
2. Convey summary of tasks to be performed by each crew member
3. Record number and type of samples identified for sampling (note any specific details as instructed by MMP)

| Sample ID | Container ID | Sample type (lvl of alt – H/M/L) |
|---|---|---|
| | | |
| | | |
| | | |
| | | |
| | | |

**NOTE**
Check Mission Log for MCC Activation Criteria **PRIOR** to Activation

4. Confirm GO for CDR MRU activation

### EV1 (CDR)

GEOPHYSICAL MRU EXPERIMENT (00:15)

1. Egress Rover
2. Unload MRU **C67** (00:02)
3. Select and place MRU at sampling site
4. Configure MRU **C67** (00:03)
   - ❑ Loosen Hypotenuse Slider friction lock
   - ❑ Partially collapse boom lifting boom feet off the floor
   - ❑ Tighten Hypotenuse Slider friction lock
   - ❑ √ Check that boom feet are clear of ground obstacles in the intended sweep path
   - ❑ Release yaw line from fairlead carabineer
   - ❑ Translate to Yaw Joint base and retrieve yaw line
   - ❑ √ Translate to Yaw Joint PIP pin with yaw line in tow
   - ❑ Check hardware clear of intended motion path and moving joints
   - ❑ Check Yaw PIP pin (1) retracted
5. Activate MRU **C67** (00:02)
   - ❑ Retrieve Anchor by opening lid of MRU
   - ❑ √ Connect Powered Driver to Anchor End Effector, check that both latches engaged
   - ❑ Anchor GeoArray to the floor by driving Anchor End Effector through Anchor Hole
   - ❑ √ Disconnect Power Driver from Anchor End Effector by simultaneously depressing both side latches
   - ❑ √ Connect Powered Driver to a Seismic Sensor End Effector check that both latches engaged
   - ❑ Check for confirmation to activate MRU

### EV2 (MMP)

GEOPHYSICAL SAMPLING (00:15)

1. Park and Egress rover
2. Unload Sampling MRU and camera (00:02)
3. Make Observations while photo documenting (00:03)
   - ❑ Report site context description
   - ❑ Environmental conditions (depth, current strength/direction, temperature, visibility)
   - ❑ Unit descriptions (distinguishing features, unit relations and orientations)
   - ❑ Variances from precursor data
   - ❑ Other notable features
4. Worksite Setup / Sample Prep (00:02)
   - ❑ Set sampling markers next to candidate samples
   - ❑ √ candidate samples are photographed
5. Collect Samples (00:02)
   - ❑ Connect Manual Driver to Rock End Effector, pushing until Latch clicks into place
   - ❑ Remove Manual driver and effector from Sampling MRU
   - ❑ Squeeze and hold handle of Manual Driver while placing over sample of interest
   - ❑ Release handle, capturing sample inside End Effector
   - ❑ Stow End Effector in Sample MRU container
6. Repeat Sampling procedures until desired samples are collected

**CAUTION**

- Avoid touching End Effectors to minimize contamination
- Latch may over extend when clicking into place

EVA - 6S - TX_S1_PRAC - IV CREW 2

Figure 4.8: Baseline DSS detailed procedure timeline - translation activity (Top) and station activity (Bottom).

content was generated from a blend of ISS and Apollo EVA activities and objectives.

The Baseline DSS incorporates only a subset of the details necessary to support EVA operations (e.g. timeline task details and supporting information) as specified in the applied requirements from TTA decision ladder. In total, the timeline artifacts themselves provide support for only three prioritized requirements. To meet the remaining TTA requirements, the IV operator must manually generate the necessary alert criteria, sets of observations, system states and address the ambiguities of execution without any specific technological support. As indicated by the red-dotted border, a critical component left for the IV operator to integrate is the relationship between timeline progress and LSS capacities.

*EVA Communication Systems*

Two forms of communication were supported in the Baseline DSS prototype: audio and text communication. An open source Voice over IP (VoIP) audio software known as Mumble/Murmur was utilized (See the Mumble website[1] for more details). Push-to-talk audio communication was provided between the EV and IV operators only. Text communication was provided between the IV operator with MCC that included a simulated 5 minute one way light time delay. The Playbook Mission Log text client shown in Figure 4.9 was provided on loan from the NASA Ames Playbook software team (Marquez et al., 2013b).

No streaming video footage was included in this prototype design. While video footage is typically utilized during present-day EVA operations, video footage is not required, per the flight rules, for present-day EVA operations.

### 4.2.2 Focus Area Integration and Walk-through

Figure 4.10 shows the Baseline DSS focus areas integrated with the expected communication traffic between all relevant flight operators. The three shaded focus areas indicate where the IV operator must direct their attention to throughout EVA execution. As de-

[1] https://www.mumble.com/

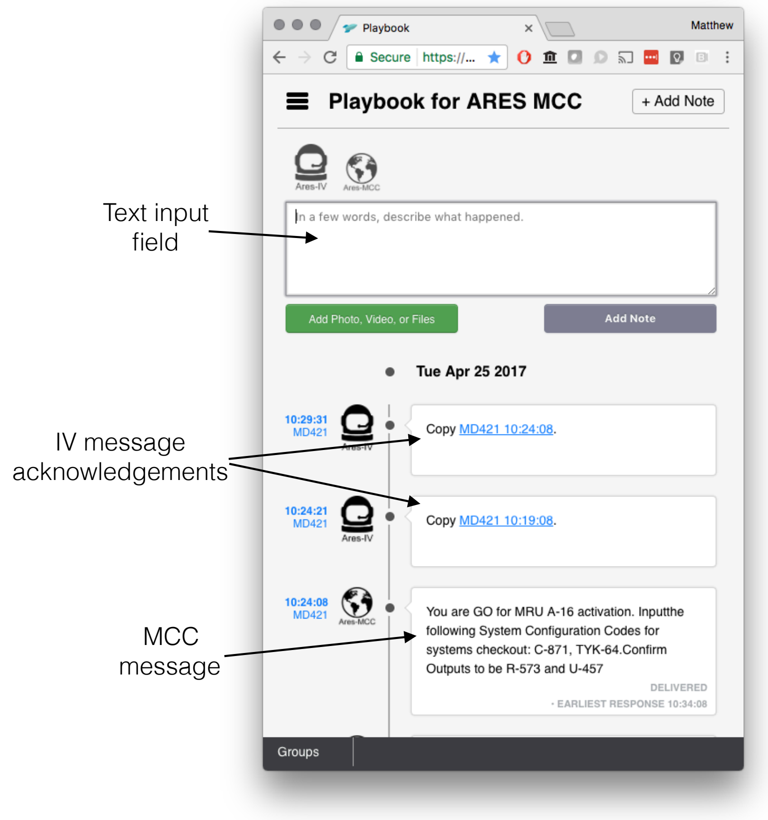



Figure 4.9: Baseline DSS Playbook Mission Log text client.

picted, each focus area is independent, thereby relying on the IV operator to facilitate the integration and association of the disparate sets of information provided by each focus area to support operations. As specified in the Contextual Design literature (Beyer and Holtzblatt, 1998), important elements to consider at this stage of design include questions such as is each focus area coherent? does the focus areas support real work? and is the work supported?

Historically, this integration effort has been performed by teams of MCC personnel (refer back to the information flow model). The Baseline DSS explores how that same level of detailed scrutiny during EVA execution could be performed by a single operator. The LSS displays provide spacesuit consumable and functionality status while the timeline provides the volume of task relevant detail to be performed. But what exactly does the IV operator do to facilitate this integration? Within this envisioned world, the IV operator is

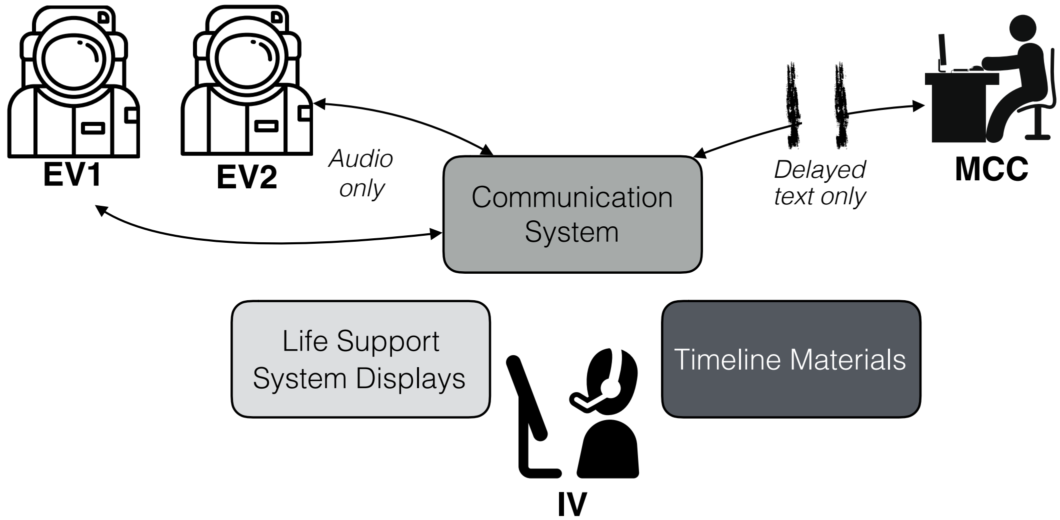



Figure 4.10: Baseline DSS integration schematic.

charged with a number of responsibilities:

- Maintain crew safety (e.g. can the LSS provide enough capability to enable the EVA to be continued without harming crew or systems?)
- Maintain timeline execution progress (e.g. are the crew successfully advancing through the timeline?)
- Integrate MCC/EV dialog and direction into the timeline and ultimately EV action

These exemplar responsibilities result in the calculation and tracking of a few critical values, as shown on the Flight Notes rubric. These calculations directly contribute to satisfying requirements TTA-28 and LSS-22 which aim to acquire a key system state understanding of overall EVA progress. Above all other constraints (under nominal operation conditions), maintaining an accurate account of overall timeline position and progress in addition to timeline margin promotes tactical decision making capabilities. To make informed decisions on how to best direct EV crew action, the EV/IV crew need to know: 1) how the actual timeline is being executed relative to the planned timeline (e.g. minutes ahead or behind) and 2) how much time the life support systems can afford and how that relates to how much time the planned timeline demands (e.g. Timeline Margin). These key variables are calculated by the IV operator using the Baseline DSS as shown in Figure 4.11.

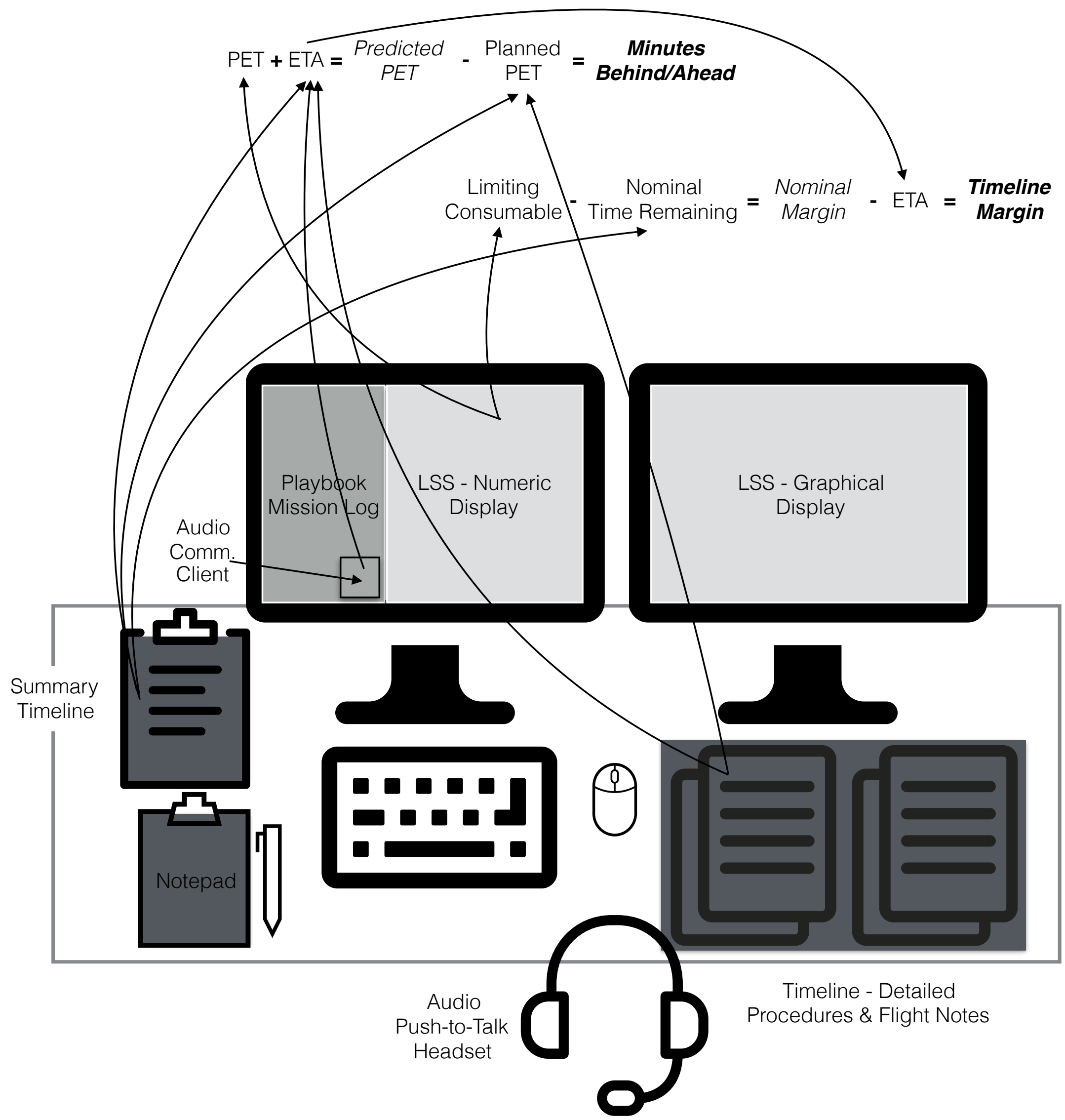



Figure 4.11: Baseline DSS walk-through depiction (Colors correspond to distinct focus areas).

The EVA PET (Phased Elapsed Time) is provided by the LSS numeric display. At the time of calculation, the EV crew are located in the timeline at a particular point and the IV operator must decide to what reference point they wish to associate to the calculation. For instance the EV crew could be nearly complete with a Translation activity, therefore the ETA (estimated time of arrival) to the end of translation could be used. The addition of those two variables yields an intermediate variable known as a Predicted PET to provide a timeline value estimate to be compared with the Planned PET, which is found on the summary timeline or detailed procedure document (depending on the reference point selected for the calculation). The subtraction of these two variables yield an instantaneous estimate of Minutes Ahead/Behind. As depicted, the Minutes behind/ahead calculation is sourced from multiple DSS components and the IV operator is charged with manually performing the time math.

Similarly, the Timeline Margin calculation follows a similar manual process of sourcing specific values from the Baseline DSS to yield an estimate. The life support system provides an estimate of the limiting consumable for each crew member from which the most limiting variable is used for the calculation. The Nominal Time Remaining value is specified value of how much time remains from the current reference point used in the ETA calculation to the planned end of the timeline. The subtraction of the two values yields an intermediate variable known as Nominal Margin. Depending on what reference point was used to perform the calculations the Nominal Margin must be offset by the ETA value used in the prior calculation to estimate Timeline Margin.

To complicate matters, the IV operator is also envisioned to be responsible for ensuring all tasks are successfully performed (e.g. obtaining verbal confirmation), responding to and integrating all MCC Mission Log messages, and recording all life support system telemetry events (from the Numerical and Graphical displays). All these actions are situated within a real-time three-way conversation with both EV crew and the IV operator. In summary, the Baseline DSS does provide the discrete components hypothesized to support EVA operations, but expects the IV operator to integrate this information to successfully generate operational utility.

A description of the Baseline DSS software code and architecture can be found in Appendix A.4.

## 4.3 Advanced DSS Development

Up to this point, DSS design solutions stemmed from heritage EVA artifacts (e.g. existing console displays and timeline products). This section explores how new designs might be applied to reshape the work that goes into supporting EVA operations as an IV operator. Specifically, a novel timeline management tool was developed and integrated with the life support system, to create a software system known as *Marvin*[2]. The digitization of the EVA timeline was a major focus of the Advanced DSS because the current method of timeline management relies wholly on paper-based products and human integration across multiple data sources, neither of which will be sustainable for future operations.

Digitizing an EVA timeline was a nontrivial effort when the aim is to make the timeline useful during execution. The transition from paper-based to digital timeline products is a major technological shift within the EVA work domain. Therefore, the majority of Marvin (Advanced DSS) development efforts focused on exploring this technological shift and the implications and benefits it can have on EVA operations, particularly from the perspective of the IV operator during execution.

Marvin is comprised of three main focus areas: life support system displays, timeline displays, and communication systems. The focus areas themselves are dedicated to the same content included in the Baseline DSS design. However, instead of being isolated, the life support system and timeline focus areas are integrated in a few key ways as described below. Figure 4.2 shows each prototype component in the form of their respective focus areas; each focus area is described in detail in the subsequent sections. Additionally, each focus area is identified based on the specific requirements they aim to satisfy. The defining characteristic of the Advanced DSS is the transition to a digital timeline management tool with automatic calculations to alleviate the burden on the IV operator to manually fulfill those requirements.

[2]Marvin is an not an acronym as typically seen with NASA programs but rather is in reference to Marvin the Paranoid Android from Douglas Adam's science fiction series: The Hitchhiker's Guide to the Galaxy. - "There's only one life-form as intelligent as me within thirty parsecs of here and that's me" - Marvin

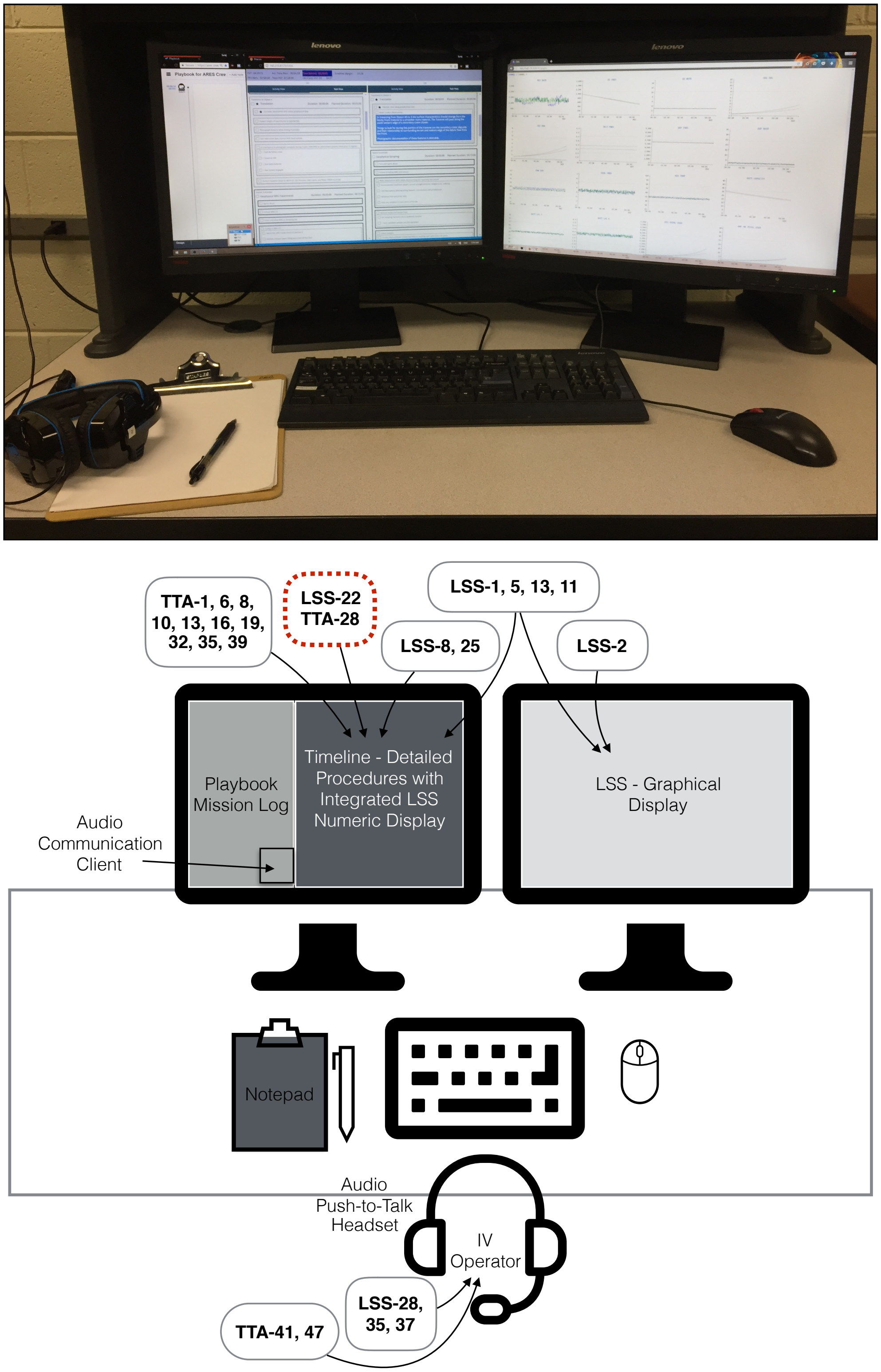



Figure 4.12: Advanced DSS, Marvin, prototype (Top) with component descriptions (Bottom). Requirement IDs are specified and organized by focus area.

The remainder of this section describes each focus area of the Marvin design is described and links the design elements to the design requirements. An integrated walk-through scenario description of an envisioned future EVA work domain is also provided to describe the expected work demands and how the Baseline DSS provides support. It is through this narrative and the subsequent simulation study that the proposed domain tools can be understood in an envisioned world.

### 4.3.1 Focus Area Modifications

Marvin consists of the same underlying information/capabilities, recast in a novel software configuration. Therefore, departures from the Baseline DSS are highlighted in the following sections.

#### *EVA Life Support System Modifications*

The LSS displays largely remain the same in terms of content. Future spacesuit systems are currently under development and their specific capabilities remain undefined. Existing ISS spacesuit and its telemetry data were maintained between the Baseline and Advanced DSS (Marvin) configuration, with some subtle user interface modifications. While there exist major avenues for development regarding the LSS area, this is an area of future work.

The numeric console display is absent in Marvin. The alerting features present in the Baseline DSS such as communication dropouts (represented by color changes) were converted to an alert symbol. The highest priority value (e.g. the most limiting consumable) was pulled from the LSS consumable summary window and included in the header (top inch of the display) of Marvin for easy reference. When an alert was triggered, an alert symbol appeared on the header to prompt user interaction by 'clicking' on the button to acknowledge the issue. Figure 4.13 shows these components pulled from the Baseline DSS numeric display configuration within the Marvin prototype.

This alerting design approach is similar to the 'dark cockpit' design philosophy where

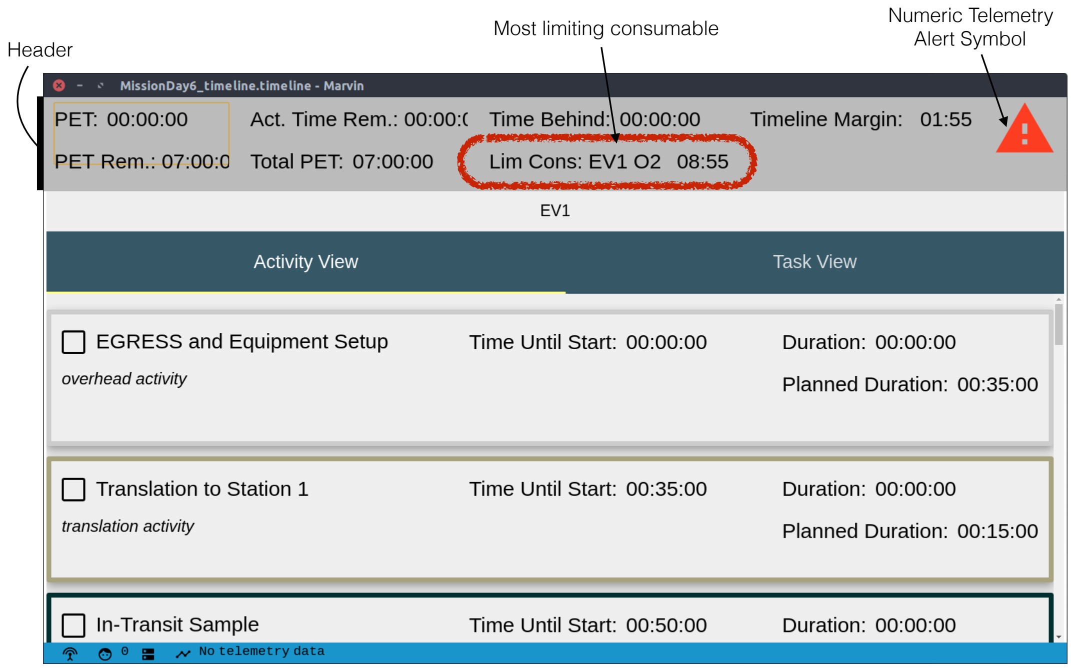



Figure 4.13: Advanced DSS Numeric display features.

the display under nominal conditions remain ‘dark’ and quiet (Wiener, 1989; Novacek, 2003). Displays become illuminated when an alert is triggered. Marvin alerts were limited to communication dropouts and values that exceeded engineering limits to again mimic the basic alerting capabilities of present-day EVA consoles. As previously mentioned, the synthesis of life support system data is currently a human-intensive endeavor. Given the lack of definition of future suits, the Advanced DSS prototype notionally represents the shift towards how future crew might begin to view and synthesize spacesuit telemetry.

The LSS graphical displays remained the same between the two configurations. Trend monitoring and analysis is a major component of spacesuit telemetry synthesis and remained unaltered from present-day practices.

In summary, the Advanced DSS LSS focus area is a combination of old and new features. The LSS numeric display design was modified to show a subset of console variables in the Header view and introduces a new alerting feature that is trigger when anomalies arise. The telemetry graphical display remained consistent between the two DSS configurations. These slight modifications represent a first step towards addressing the many potential avenues that exists to layer and present subsystem information and to include advanced analytics to support LSS data synthesis and processing, however it has been left for future work.

### *EVA Timeline Artifact Modifications*

#### Considerations for Digitizing EVA Timelines

Digitizing the timeline requires an examination of how a timeline can evolve throughout EVA execution. Figure 4.14 shows a generic summary timeline described in two categories that relate to the tasks being performed and time when they are performed. As a result of knowing both the temporal and task distributions, the timeline can maintain coordination amongst all EVA operators. It is the integration of these two components that enables a reference to be made between actual execution and what was scripted. In an ideal world, every single planned task would be performed exactly when it was scheduled. However, EVA execution rarely goes as planned and timeline progress can evolve in multiple ways. Tasks may be added/dropped, reordered or modified while the timing of events may deviate from schedule (e.g. crew perform tasks faster or slower than expected or tasks are modified, thereby resulting in temporal shifts). These timeline deviations must be expected in future missions; therefore, a digital timeline tool should be capable of coping with and supporting this variation. With respect to the insights found in Chapter 3, specialized EVA operators within MCC currently cope with this timeline variation throughout execution.

Furthermore, consideration must be given to sheer volume of tasks that are scripted in an EVA timeline. Every moment, of every EVA, ever performed by NASA is scripted and continually assessed to ensure adequate and safe progress is being made. Figure 4.15 shows the timeline from Apollo 17 EVA 1 which is representative of one of the only planetary surface EVAs dedicated to scientific exploration and is representative of what future EVAs might entail. Seven hours of tasks are scripted in this timeline using a variety of descriptions and details to direct crew actions.

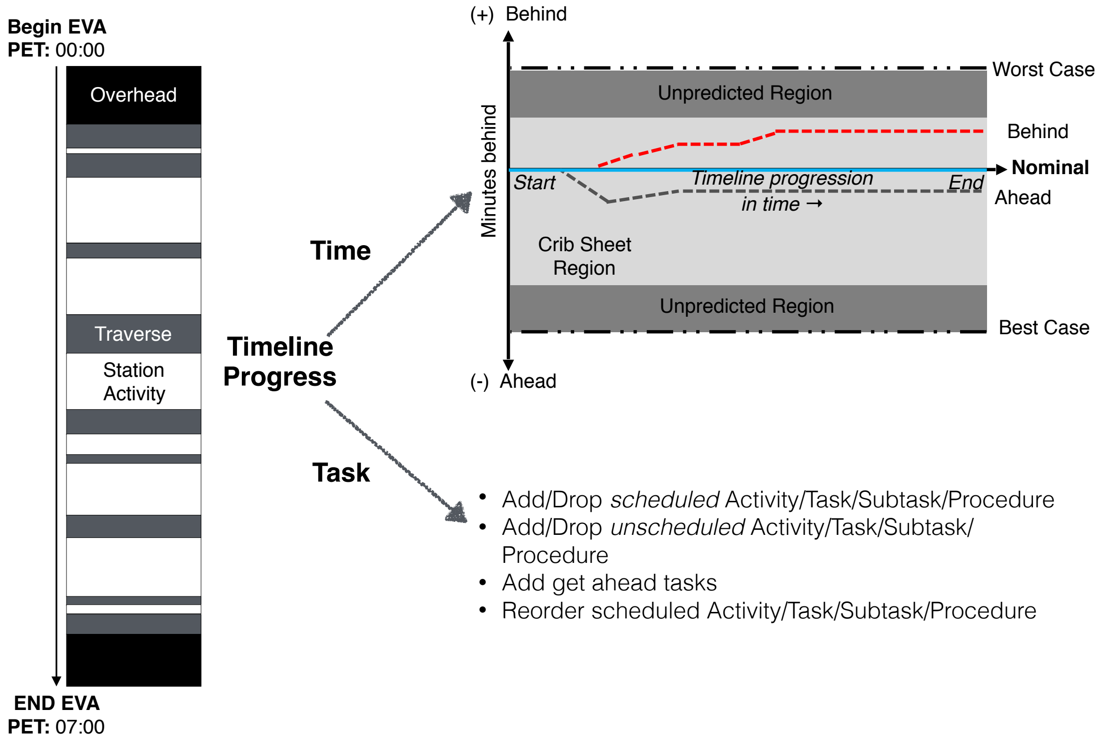



Figure 4.14: Notional EVA timeline execution evolution.

Similar levels of timeline detail and structure still hold true for present-day ISS EVA operations. Therefore, if a timeline is to be digitized, tasks within timelines must be decomposed into appropriate units that reflect this variety of task detail. These intrinsic units of action descriptions are shown in Figure 4.16 where the generic term Task is decomposed into a hierarchy consisting of 4 levels (Activity, Task, Subtask, Procedure). The Activity level is considered the highest level of abstraction that describes crew actions. The Task level in this hierarchy is considered as the second level of abstraction that is used to provide more detail regarding its parent Activity. The SubTask level in this hierarchy is considered as the third level of abstraction, used to describe its parent Task and finally the Procedure level in this hierarchy is considered as the lowest level of abstraction used to describe the discrete events and details required to satisfy or complete its parent Subtask. Establishing a common set of timeline descriptor levels is an important first step to standardizing the timeline in a digital format. Fortunately, EVA timelines lend themselves to a detailed

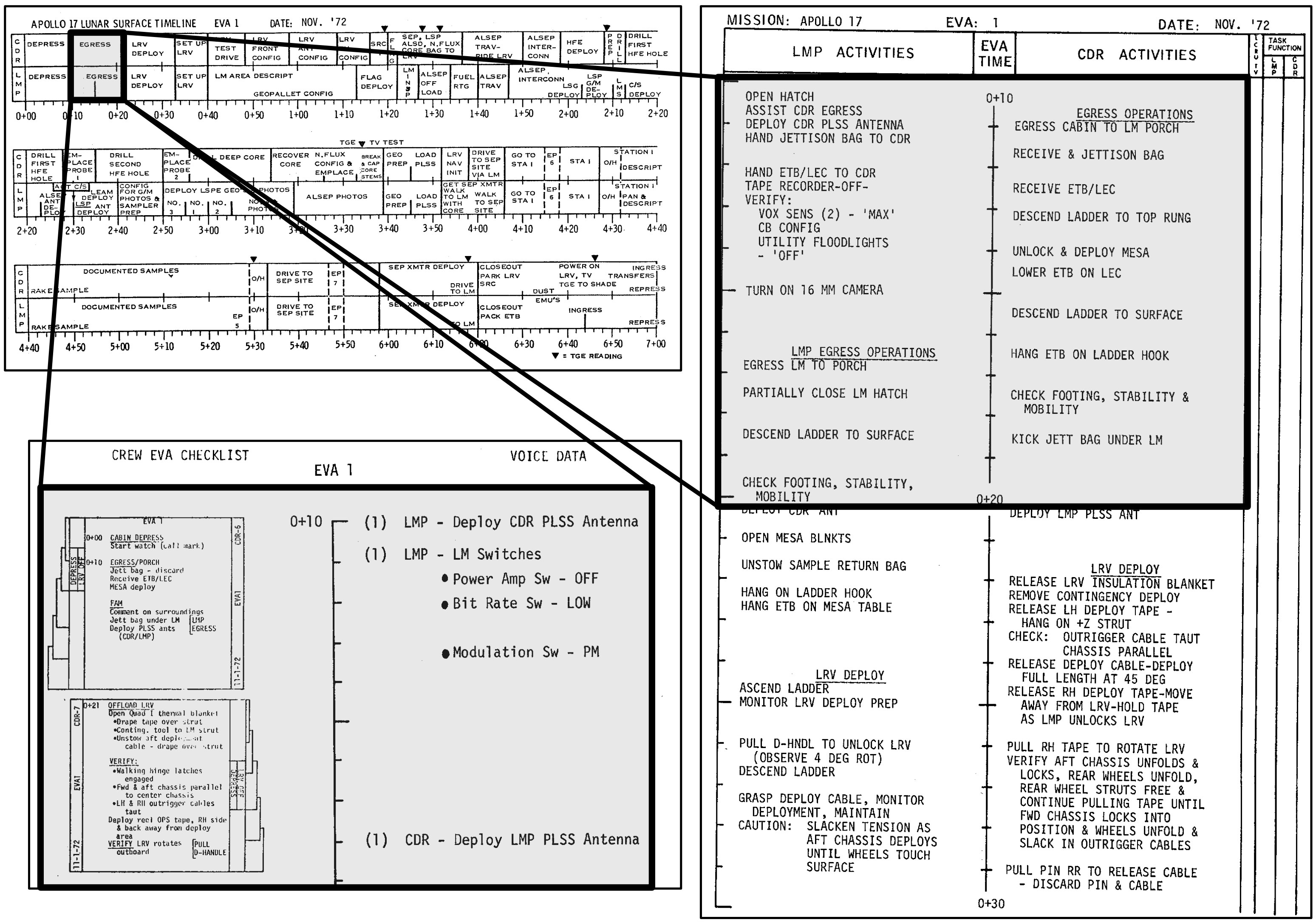



Figure 4.15: EVA summary and detailed procedure excerpts of Apollo 17 EVA 1 timeline, see Miller et al. (2016a, 2017a) for detailed descriptions of Apollo timelines.

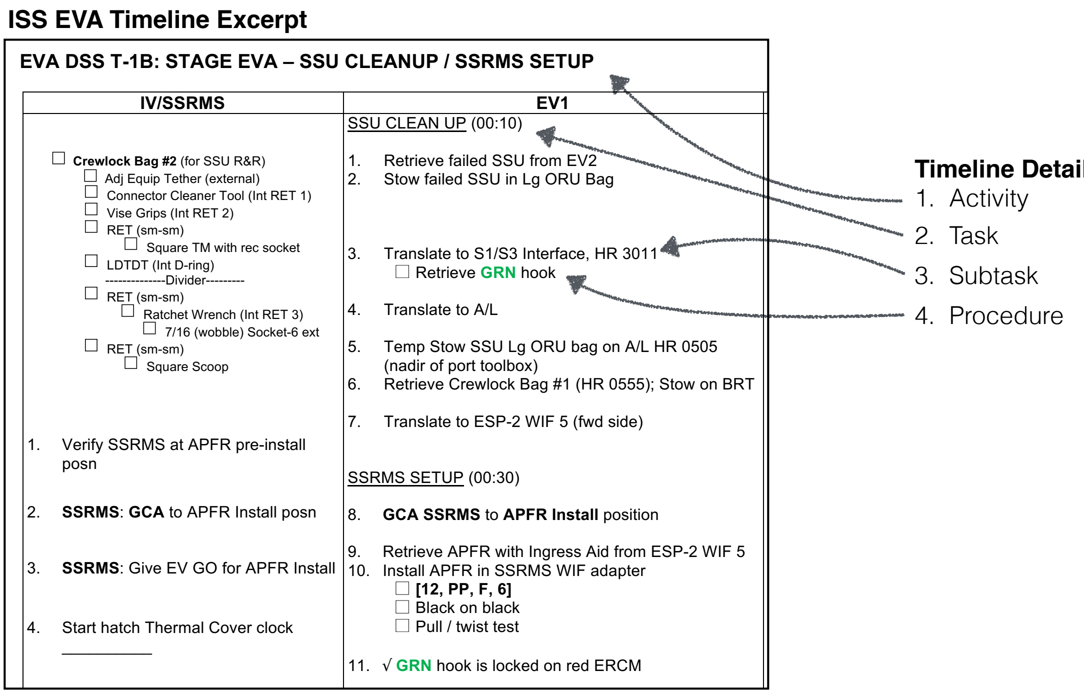



Figure 4.16: EVA timeline task decomposition derived from ISS EVA timeline structure.

hierarchical decomposition such as this due to their highly structured and coordinated arrangements.

**Activity**:

- Characteristics include: title/description, time duration, priority (usually sequenced amongst the other priority activities)
- Each operator is assigned activities (EV1 or EV2)
- Minimum duration interval for activities can range from 5 to 60+ minutes
- Activities typically have lower level of abstractions used to describe the minutiae

**Task**:

- Characteristics include: title/description, time duration, priority (usually sequenced amongst the other priority activities)
- Tasks and Activities can have identical attributes. Most times however, multiple tasks comprise a single activity (Parent/Child relationship)
- Minimum duration interval for tasks are typically no smaller than 2-5 minutes

**SubTask**:

- Subtasks usually consist of a sequenced set of descriptions ranking in the order of operations that consist of Verb/Noun descriptors
- Subtasks are explicitly associated to a particular Task (Parent/Child relationship)
- The number of subtasks can vary and is highly Task dependent
- Do not typically have a time duration (considered as discrete events)

**Procedure**:

- Procedure usually consists of a sequenced set of actions
- Checkboxes provide a means to cross out procedure when completed
- Procedures are explicitly associated to a particular SubTask (Parent/Child relationship)
- The number of Procedures can vary and is highly SubTask dependent
- Do not typically have a time duration (considered as discrete events or desired states)

The content and leveling of descriptions is heavily dependent on the complexity of the actions and stems from the EVA objectives themselves. In some cases, the timeline might follow a tight linear sequence of actions such as those found with engineering objectives. Other times, the timeline might exhibit iterative or more ambiguous periods of time. Examples of this iterative timeline description can stem from science objectives that might involve general survey and exploration of a general location such as those found during the Apollo program (Miller et al., 2017a). This volume of detail is highly variable, therefore a digital timeline should be able to support all timeline details to the appropriate levels necessary for successful execution.

At this stage of design, I focused the remainder of this thesis on how can we support the simultaneous integration of timeline position with temporal positioning without modification to the action descriptions. In other words, I did not specifically investigate nor promote the structural alteration of actions within the timeline but rather explored how a digital timeline could begin to become aware of the temporal progress made during EVA execution. Static EVA timelines were constructed and effectively 'fixed' during EVA execution and the specific HITL experimental scenarios modulated the tempo of execution, thereby modulating the temporal evolution of timeline execution without restructuring timeline actions.

Marvin incorporates a novel digital timeline to support EVA operations. The advanced timeline fully digitizes all timeline components. The same hierarchical structure of EVA task description (as first introduced in Chapter 3) is now embedded in Marvin and is fully expandable to meet any level of task description. In other words, EVA timeline descriptions can be specified at the Activity, Task, Subtask, and/or Procedure level. Only text description is currently supported in this version of Marvin, but is readily extensible to additional descriptors such as images and video. Figure 4.17 shows the Activity and Task timeline views of Marvin. The Activity View replaces the summary timeline artifact and the Task View replaces the detailed procedures document from the Baseline DSS. The Flight Notes sheet is no longer needed in the Advanced DSS because those features are embedded within the code logic of Marvin itself. The highlighted regions are described in more detail in the subsequent figures.

Figure 4.18 shows an expanded view of the specific variables included in the header. The header provides a persistent reference location of pertinent EVA variables for an IV operator to maintain adequate awareness throughout EVA execution. Note that the data in the header shows the more constraining EV crew's progress (i.e. shows the longer duration of the two EV crew members). Each variable is briefly described below. All time formats are Hours:Minutes:Seconds unless otherwise specified.

- PET: Phased Elapsed Time that counts up continuously from official start of EVA.
- PET Rem.: Phased Elapsed Time Remaining that counts down from the total planned remaining duration EVA timeline. Clock will stop counting down when crew accumulate minutes behind schedule (due to a step taking longer than expected) so that an accurate estimate of planned remaining timeline is quantified.
- Act. Time Rem.: Active Time Remaining refers to the time remaining for the current Activity.
- Total PET: Total Phased Elapsed Time of the EVA timeline as performed. Will increase or decrease throughout execution based on the crew's performance relative to the planned step durations.

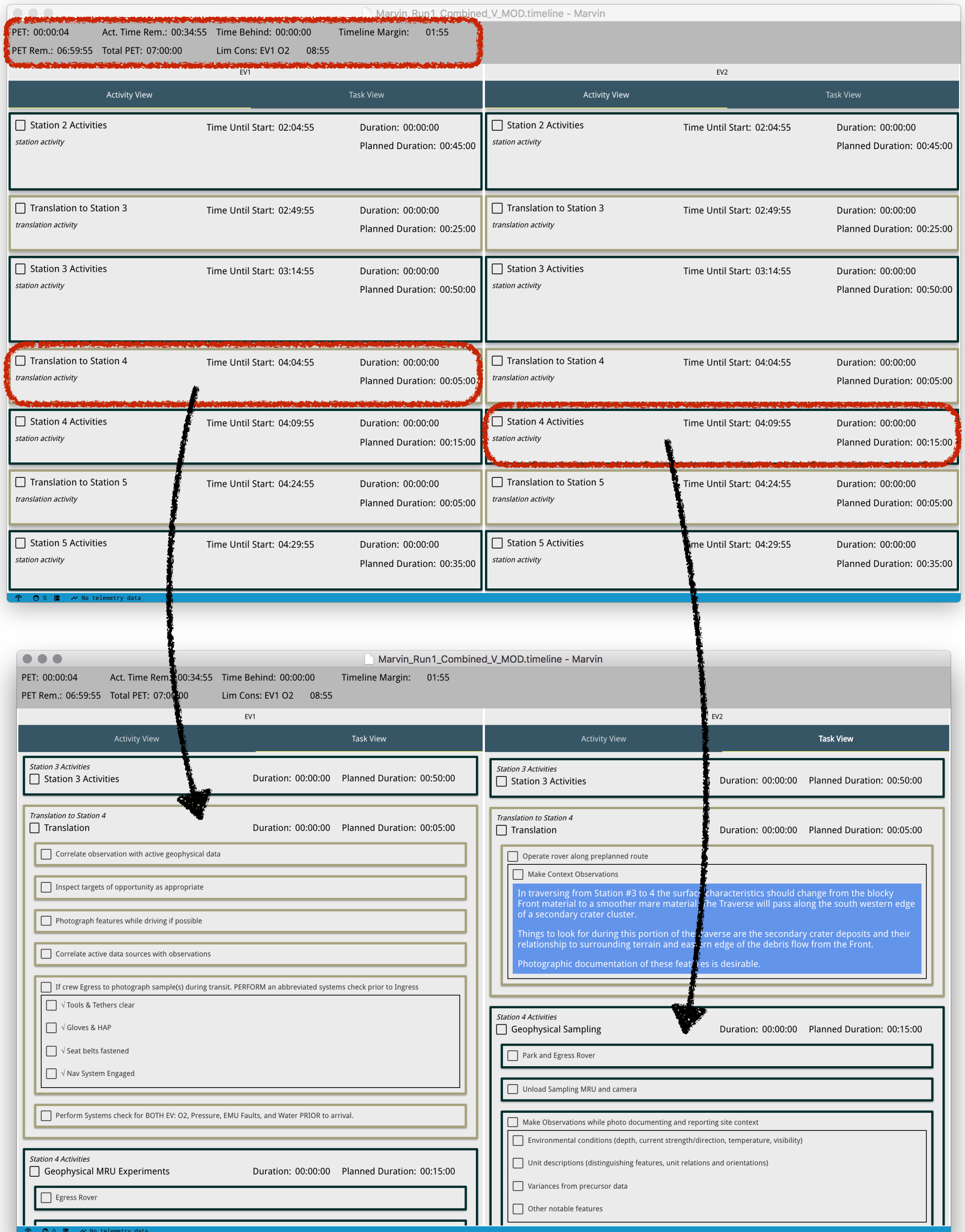



Figure 4.17: Advanced DSS Timeline Activity View (Top) and Task View (Bottom).

- Time Behind: Estimates the time behind schedule of crew execution. In the event of becoming ahead of schedule, this value will be negative.

- Lim Cons.: Limiting Consumable is the resource between the two crew members that will expire first. The EV crew and specific limiting consumable is shown alongside the estimated PET.

- Timeline Margin: Calculated from subtracting the remaining PET from the limiting consumable estimate to provide an overall estimate of usable time beyond the time demanded by planned timeline.

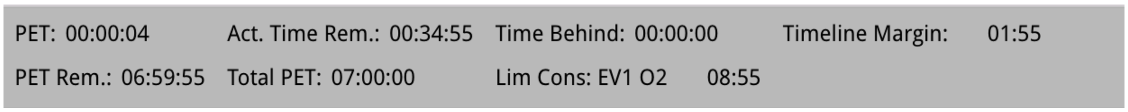



Figure 4.18: Advanced DSS header view.

Two different activity types, Translation and Station Activity, are shown in Figures 4.19 and 4.20, respectively. The Activity view provides overall descriptions of the timeline such as the activity type, the estimated time until start from the current EV position in the timeline as well as shows the planned and as-performed duration of execution. The Task views provide a more detailed compilation of the specific Tasks, Subtasks, and Procedures pertinent to a particular Activity. Nested borders visually demarcate the child/parent relationships between the descriptions. Alongside each description is a checkbox where the IV operator can click to signify that specific step has been completed. Through the act of checking off steps on the Timeline, Marvin is capable of assisting the IV with comparing the actual timeline being executed to the planned timeline (See next subsection for more detail.)

Figures 4.19 and 4.20 show a subset of the variety descriptions that could be used to define an EVA timeline. These descriptions are representative of both the general and specific details that must be accommodated or performed during EVA execution by the EV crew.

*Internal Marvin Timeline Logic*

Each level of the timeline is structured as a generic step with the classification of one of the four descriptor types: Activity, Task, Subtask, or Procedure. With this designation along

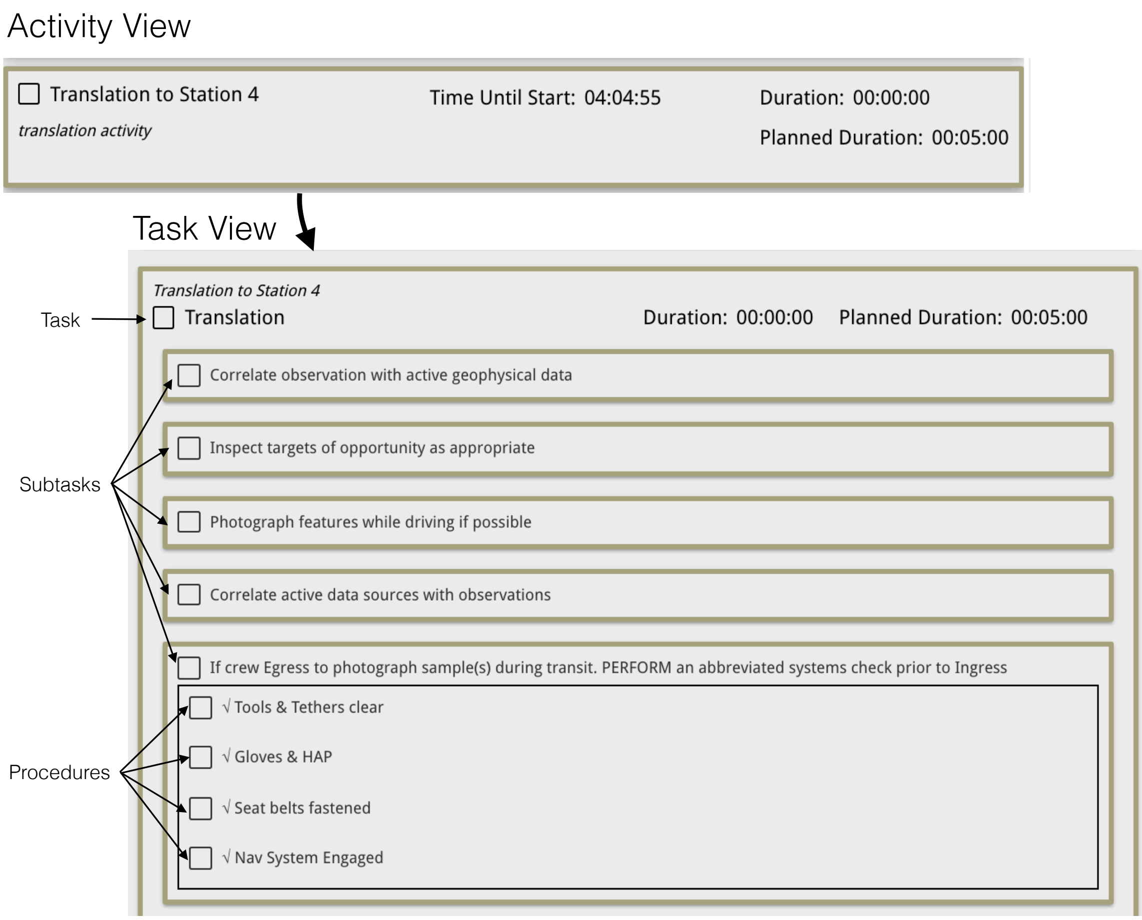



Figure 4.19: Advanced DSS translation view for EV1.

with some other attributes shown in Figure 4.22, a compiled EVA timeline is digitally generated. A Parent/Child relationship is established based on the descriptor designation to define the specific branches of steps. Figure 4.21 shows a notional branch structure for an EVA timeline that consists of one Activity with two Tasks, where each Task contains two Subtasks and subsequently two Procedures each.

A generic Step in this data structure includes attributes that describe the corresponding segment of the EVA. Figure 4.22 shows the generic Step attributes used for timeline generation alongside an example script used by Marvin to represent the timeline. Each Step is assigned a description, which is what users read in the timeline view.The Step is also assigned to a channel corresponding to EV 1 or 2. The dependency between Steps is specified directly by the nesting other Steps inside the children attribute within a par-

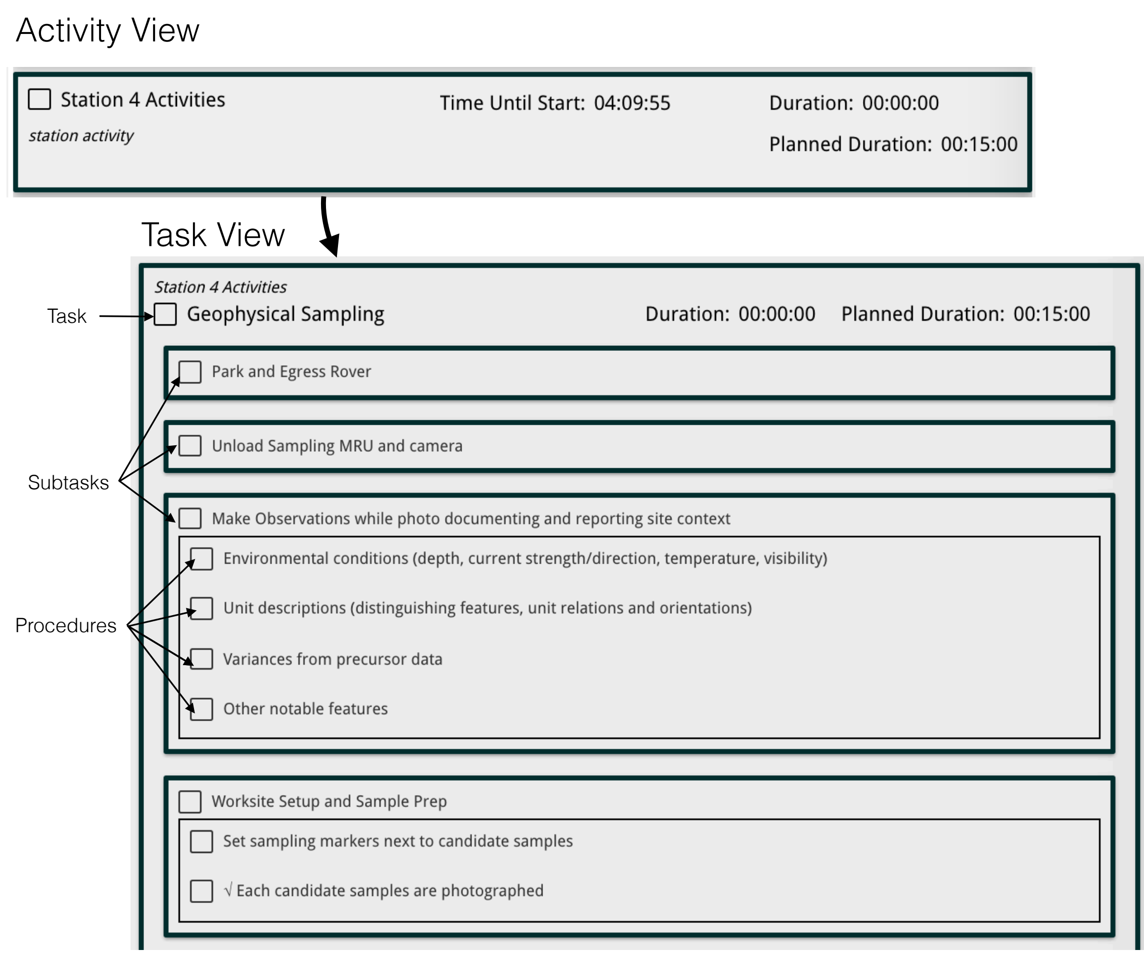



Figure 4.20: Advanced DSS station view for EV2.

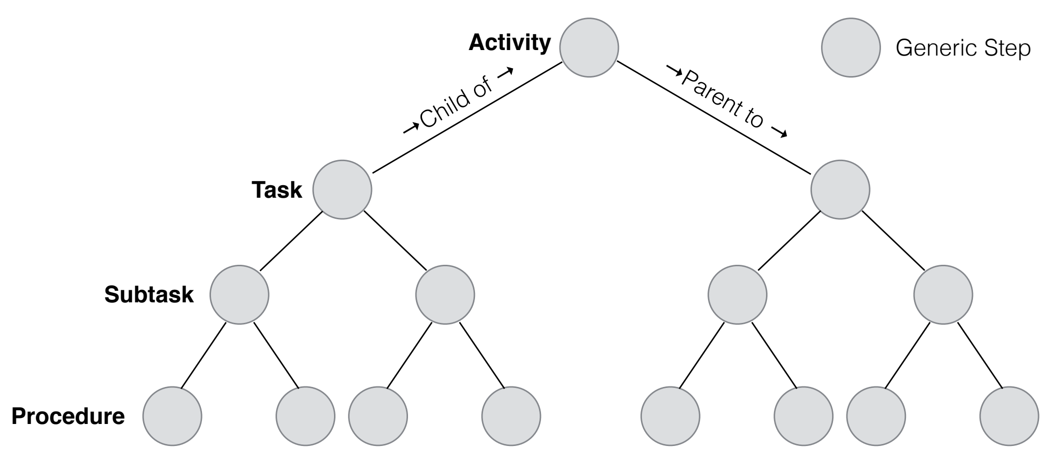



Figure 4.21: Advanced DSS internal timeline structure.

ent Step. Other attributes include how long the step should be (duration), the child/parent relationship (dependency), and importance of the step (priority).

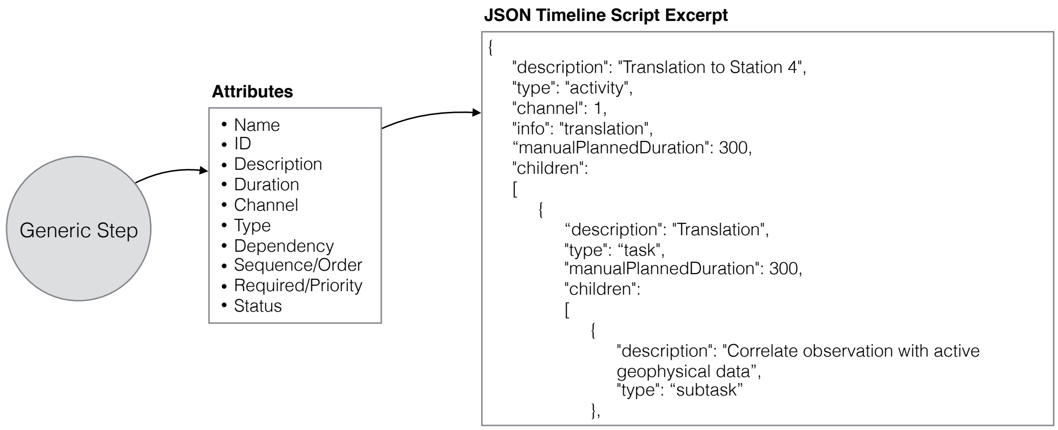



Figure 4.22: Advanced DSS generic timeline step attributes.

While this example is symmetrical, symmetry is not required. The lowest level of descriptor detail is provided as necessary for the particular parent step being defined in the timeline. Figure 4.23 shows an example of where one Subtask does not include any children (e.g. Procedure Steps). Marvin will treat this alternate timeline the same with regards to timeline tracking and progress estimation.

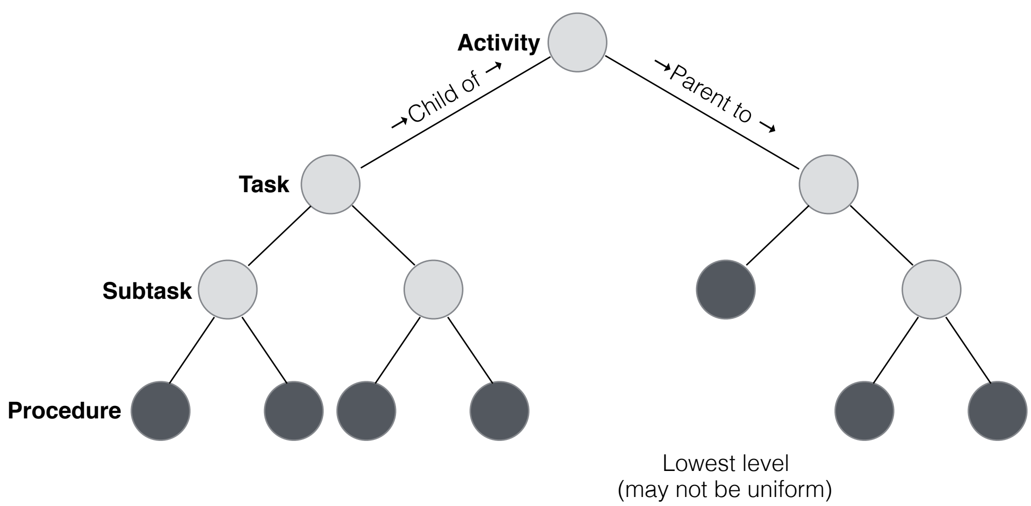



Figure 4.23: Alternate Advanced DSS internal timeline structure.

In order to perform the calculations for the variables shown in the header, the Advanced DSS generates a linear timeline at each instance of interaction throughout EVA execution. In other words, when a step is checked off, Marvin performs an updated comparison between the actual and planned timeline information. During the periods between interaction, Marvin's internal clocks count upwards based on the current active step. Figure 4.24 shows an example of how Marvin views the linear timeline at a given position in timeline execution (the vertical dashed line indicated where a step has just been completed). The planned timeline is compared to the actual timeline progress made (when the step is checked off) thereby computing a remaining planned timeline from that reference point. The highly scripted nature of EVA timelines lend themselves to making this comparison frequently throughout execution. Activities and Tasks are typically quantified on the order of tens of minutes upwards to hours in duration. Subtask durations are typically on the order of minutes.

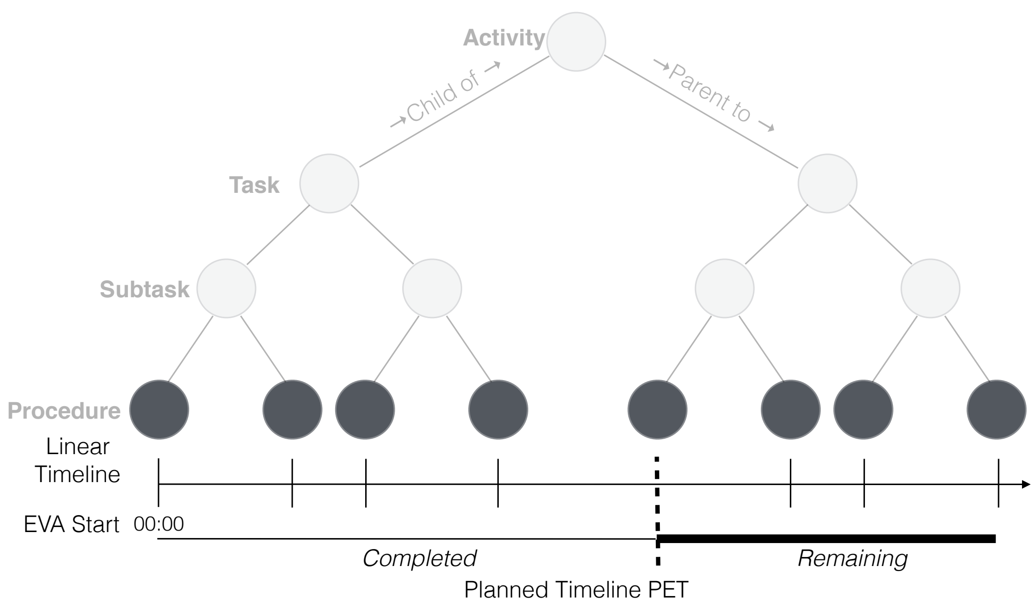



Figure 4.24: Advanced DSS linear timeline with lowest level steps utilized to perform timeline calculations.

The Advanced DSS provides the ability to digitally track timeline progress as a consequence of the IV checking off steps similar to how steps were crossed off in the Baseline DSS timeline artifacts. The IV works collaboratively with the Advanced DSS as part of their workflow to maintain an accurate representation of what the EV crew are doing when so that an accurate estimate of minutes behind and timeline margin is automatically calculated.

At this point, some additional detailed assumptions must be made to fully specify the currently functionality of the Advanced DSS timeline management focus area:

- Timeline order of steps is arranged from Top to Bottom.
- Time duration attribute does not have to be applied to all steps.
- Marvin equally distributes the duration assigned to a parent's children if no lower level duration is assigned to the lowest level children. Durations are typically assigned only to the Activity, Task, and sometimes Subtask levels. Procedures are commonly discrete events where 'duration' doesn't make a whole lot of sense.
- Timeline step restructuring is currently not supported. Once a timeline is made and EVA begins, only the tempo of execution can be adjusted
- Autocompletion lets all children be autochecked when its parent is checked off. If all children are individually checked off then their shared parent will automatically be checked off. In the case where a step is purposefully skipped or not verified, Marvin internally distinguishes between what steps were actually checked-off versus by the IV operator those that were autocompleted. The system is currently configured to require all steps be checked off using either method to accurately estimate EV crew position in the timeline.
- Time is conserved throughout execution. There are no 'gaps' or 'pauses' in time dedicated to performing the timeline and time dedicated not to performing timeline objectives.
- Timeline Steps do not necessarily have to be executed in the specified timeline sequence.

Additional Marvin code logic and architecture description is provided in Appendix A.4.

*EVA Communication System Modifications*

No changes were made to the audio or text communication systems described in Section 4.2.1. The Advanced DSS assumes audio only communication between the EV and IV crew and time delayed text communication between MCC and the IV.

#### 4.3.2 Focus Area Integration and Walk-Through

Figures 4.25 and 4.26 shows the primary linkage built between the focus areas in the Advanced DSS prototype. Timeline progress is captured digitally by the system and combined

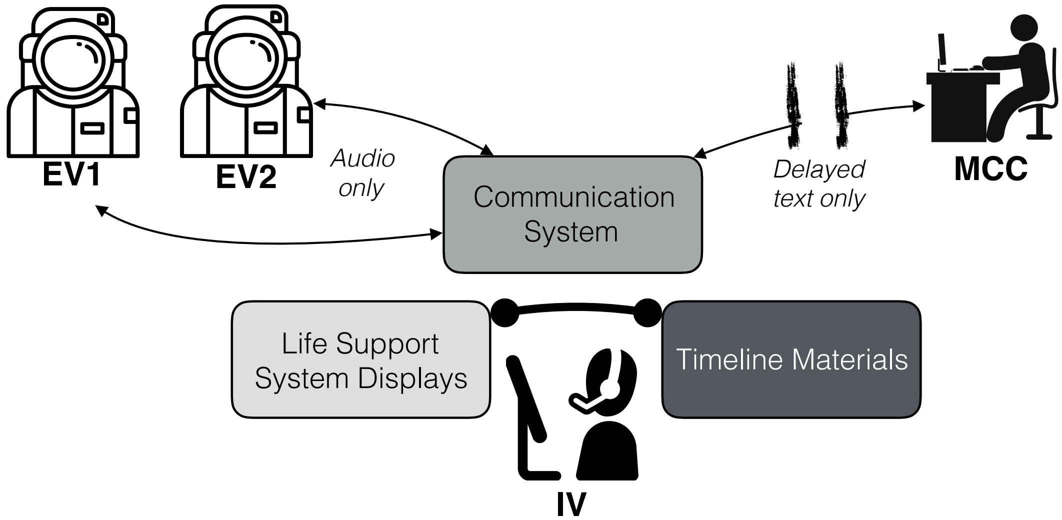



Figure 4.25: Advanced DSS integration schematic.

with elements of the life support system focus area so that overall progress calculations (e.g. minutes ahead or behind and margin) can be performed by the system. Again, it is important to examine each focus area As discussed in the Contextual Design literature (Beyer and Holtzblatt, 1998), to understand if each focus area is coherent? does the focus areas support real work? and is the work supported?

The aim here is to demonstrate the utility of this linkage and why it is so critical to EVA operations. The Advanced DSS as depicted in Figure 4.26 provides a new way of thinking about how to address the critical requirements specified in TTA-28 and LSS-22. The reality of EVA operations is that execution almost never goes exactly as planned and the DSS is expected to support this off-nominal tendency and must be able to cope with execution deviations. Currently, the Advanced DSS can handle *time* related perturbations in timeline execution. In other words, by simply checking off when a particular step is completed by the EV crew, an instantaneous snap shot of timeline progress can be made to a planned timeline with summary information provided to the IV operator. Additionally, the consumption of life support consumables can be difficult to predict, therefore integrating the most up-to-date account of consumables usage is imperative to maintaining accurate awareness of operations progress. The IV operator can now maintain execution progress

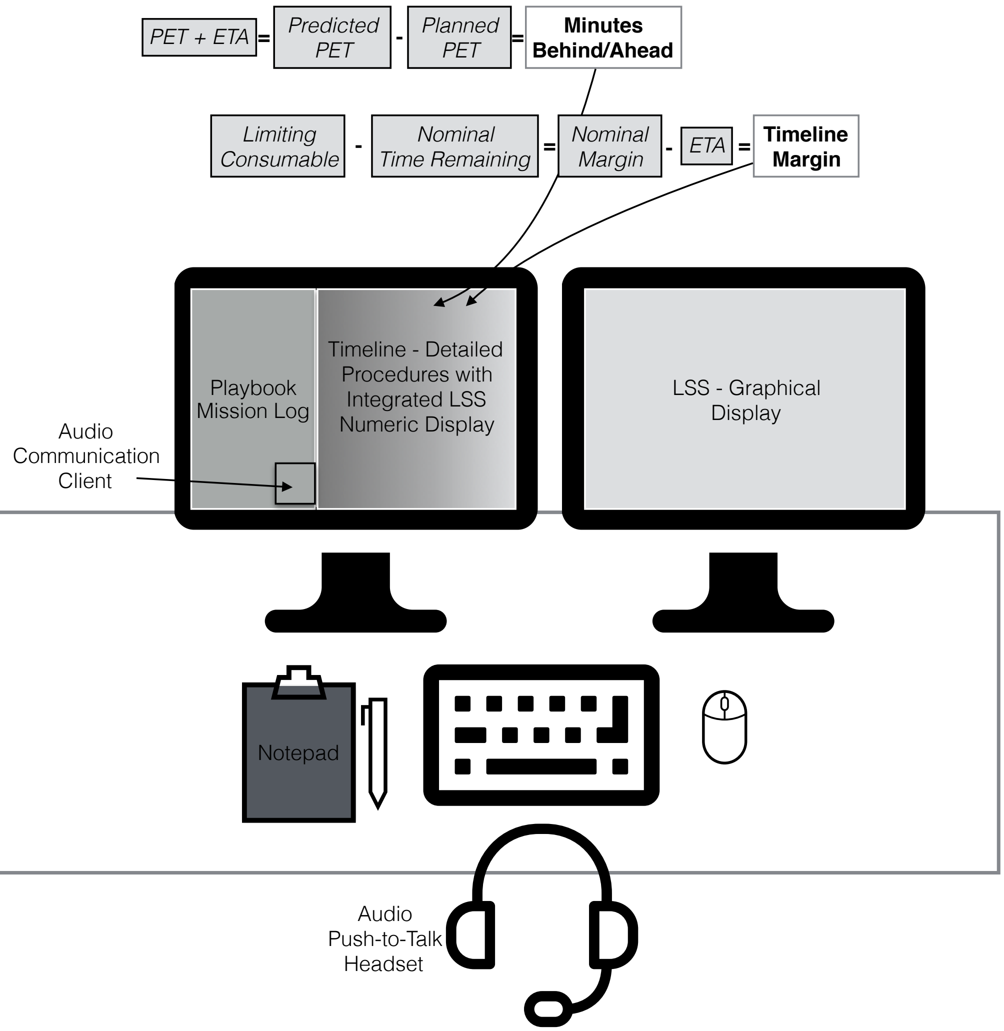



Figure 4.26: Advanced DSS walk-through depiction (Colors correspond to distinct focus areas).

and how it relates to the life support system capacities at a glance as opposed to manually performing time-math calculations.

Furthermore, by checking-off steps throughout execution, the IV operator not only tells Marvin where the EV crew are in the timeline and in return obtains operational constraint information, that interaction now becomes a potential medium of communication amongst the entire flight team that could extend beyond the IV operator workstation. Instead of a handwritten record of timeline execution as found in the Baseline DSS, the Advanced DSS enables the generation of digital record which could be leveraged to share with both the EV crew as well as with support personnel in MCC. In effect, a context dependent exchange of information, never previously available to the EVA work domain could be leveraged to promote EVA execution. But before those future capabilities can be realized, a foundational understanding in what demands shape EVA execution must be obtained and reflected early in the system design process as highlights in the Advanced DSS prototype.

## 4.4 Summary - Linking the DSS to Requirements and Envisioned Simulation Environment

> "Good designs should come from an understanding of how the application will be used (Carroll, 1991, p. 234)."

In this chapter, two complementary DSS prototype designs were defined to support EVA operations. The designs were intended to be used by an IV operator, who is situated as the *field marshal* of EVA execution with the responsibilities of timeline, life support system, and communication management. Each of these three focus areas were defined individually as well as in combined walk-through scenario descriptions for each prototype and differences in the designs were discussed. As Carroll 1991 stated above, incorporating how the system will be used is a necessary part of successfully achieving desired designs.

Table 4.2 shows a summary of how the particular design solutions were proposed to meet the prioritized requirements. The Baseline DSS expected the IV operator to manually fulfill and meet the specified requirements. Specifically, the IV operator was expected to manually estimate and integrate EVA data to satisfy both LSS-22 and TTA-28 requirements. As for the Advanced DSS, the digitization of the timeline artifacts opened a host of technological capabilities that could now be applied to satisfy many of the TTA and LSS requirements previously left to the IV operator in the Baseline design. Most notably is the Advanced DSS provided the capability to obtain the system state understanding necessary to address LSS-22 and TTA-28 and make it transparent to the IV operator.

Table 4.2: Comparison of DSS design elements to the requirements they aim to satisfy.

| | | Requirements (ID) | |
|---|---|---|---|
| DSS | System Elements | LSS | TTA |
| Baseline | **Life Support System** | 1, 5, 13, 11 | |
| | LSS-Numeric Display | 8, 25 | |
| | LSS-Graphical Display | 2 | |
| | **Timeline Artifacts** | | 10, 13, 16 |
| | Summary Timeline | | |
| | Detailed Procedures | | |
| | Flight Notes | | |
| | **IV Operator w/Communication System** | **22,** 28, 35, 37 | 1, 6, 8, 19, **28,** 32, 35, 39, 41, 47 |
| Advanced | **Life Support System** | 1, 5, 13, 11 | |
| | LSS-Graphical Display | 2 | |
| | **Timeline Artifacts** | **22** | 1, 6, 8, 10, 13, 16, 19, **28,** 32, 35, 39 |
| | Detailed Procedures w/Integrated LSS Numeric Display | 8, 25 | |
| | **IV Operator w/Communication System** | 28, 34, 36 | 41, 47 |

Finally, the prototype designs described in this chapter serve to establish grounded exemplars of what future 'fully-featured' DSS designs might entail. The prioritized requirements addressed in Table 4.2 purposefully leave room to incorporate new variables to account for what future EVA systems may impose on EVA operations (i.e. new spacesuit or spacecraft constraints). While the proposed prototypes may not fully satisfy the prioritized requirements, they do instead provide a platform upon which more resolution and detail might be integrated in a meaningful way in future design iterations.

Throughout this chapter, an emphasis was placed on scrutinizing each DSS prototype design feature for what it provides within the context of envisioned operations. Each prototype is attentive to the realistic volume of details contained within each of three focus areas. As described in the following chapter, each prototype is examined in a realistic future EVA scenario to test the hypothesis that the Advanced DSS does lead to more proficient IV operator support.

# CHAPTER 5

# EVA DECISION SUPPORT SYSTEM ASSESSMENT

The challenge at this point in the design process is how can we test the prototypes in a work domain that does not yet technically exist? One approach is to construct the hypothesized future domain. However this is a challenging proposition given the vast number of dimensions to consider. This *envisioned world problem* involves first acknowledging that the envisioning process itself can have significant impacts on the potential conclusions drawn on system designs. It is therefore imperative that as much care and attention is given to the creation of this future domain as the prototype designs themselves. As described in Chapter 2, this process involves addressing four initial considerations for effective domain construction: Pluarlity, Underspectification, Groundedness, and Overconfidence to vet the domain to help curb against inaccurate design conclusions. A domain like EVA is much too complex for one single study to address, but we can make progress by making reasonable assumptions about what to focus on now and what might be better left to future work. Woods suggests beginning the derivation process by first addressing these four considerations by incorporating a variety of observational stages as shown in Figure 5.1.

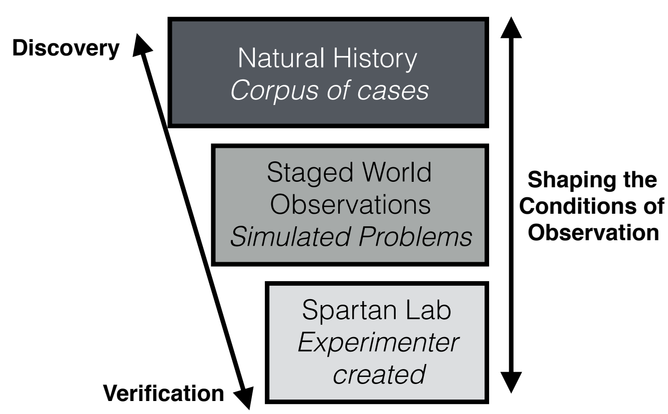



Figure 5.1: The variants of shaping the conditions of observation (Woods, 2003, p. 41).

As a result, the construction process is arranged in three stages: Natural World, Staged World, and Spartan Laboratory. The assertion is a more realistic Spartan laboratory setting can be developed based on the insights observed by studying the Natural and Staged Worlds. As a result, "Insight provides the linkage between field research techniques as discovery processes and laboratory research techniques as verification processes (Woods, 2003, p. 50). The first part of this chapter is dedicated to how I approached my envisioned world problem and how I utilized Natural/Staged Worlds as a means to construct my Spartan Laboratory environment. The remainder of this chapter is dedicated to the human-in-the-loop experiment performed in my Spartan Lab to assess the proposed prototype design solutions.

## 5.1 Translating the Current EVA Work Domain to an Envisioned One

Figure 5.2 shows the discrete activities that contributed to the construction process of the envisioned EVA domain. The remainder of this section is dedicated to elaborating on these insights obtained from the Natural and Staged World observations and how those insights influenced the construction of the Spartan Laboratory environments.

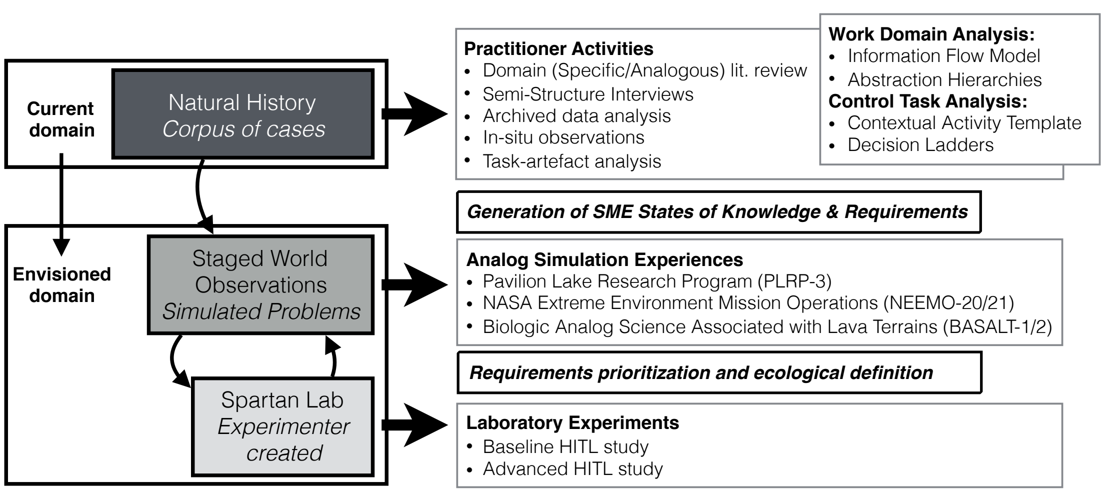



Figure 5.2: The envisioning process decomposed into Natural, Staged, and Spartan settings.

### 5.1.1 The Natural History of EVA

Chapter 3 was dedicated to the study of the Natural History of the EVA domain. Using the CWA framework, I incrementally examined the domain to derive design requirements that reflect the cognitive and information demands that exist now and will persist in the EVA work domain. Two DSS prototype solutions were then developed to meet a subset of those specified requirements. As with any design endeavor, establishing a realistic baseline prior to the solution generation process helps ground and justify design choices. This process involved a comprehensive examination of the the intrinsic work demands and constraints that exist in the current work domain. I then identified two key work functions that will likely need to be reassigned to a new agent (TTA and LSS). Requirements were then formulated from DL's of SME SoK's to shape prototype development efforts, at which point two prototype designs were constructed based on those specified requirements. Additionally, I began to build relevant scenarios surrounding the use of those prototypes and identified the agent most appropriate to take on those new work responsibilities while using the prototype designs.

This stage of analysis was important for a number of reasons:

- A clear purpose for technology development was established. I did not rely on some other study. This purpose was derived from a broad, and iteratively more tailored understandings of the demands of the EVA domain as it exists today.
- A set of requirements was generated and parsed to set goals for design solutions to meet.
- Basic scenarios and potential user of the technology was identified to help describe, justify, and motivate the particular shifts that may occur.

This last step is where most studies continue into a hypothesized work domain with solutions in hand and then talk about all the experimental results without really verifying that their envisioned world is appropriate. Often a single SME or focus group is relied upon to verify envisioned worlds. To try and address the 4 challenges of the envisioned world problem, I leverage the staged world setting to help prioritized components of my spartan lab to guard against these challenges.

### 5.1.2 Staged World Construction: NASA Analog EVA Operations Experiences

The envisioning process is a collective endeavor in translating existing domain attributes into a future context. A vital component of the envisioning process is the iterative and collaborative construction process that ultimately yields a future work domain. As a designer, I participated by immersing myself in already active areas of research who were performing similar EVA development efforts. My goal was to leverage existing envisioning efforts as a means for me to more precisely define the attributes of a realistic HITL simulation envisioned needed to test my developed DSS prototypes. This goal led me to my participation in numerous NASA analog research programs as described in Table 5.1. In total, I observed and participated in over 175 cumulative hours of simulated future EVA operations experience through these NASA sponsored research programs. As part of the scientific and engineering teams from these large staged world environments, I was able to gain perspectives and insights from the community at large who is was already thinking about future EVA operations.

Staged World construction is not a trivial task, but is a necessary to construct a realistic Spartan Laboratory setting. This is particularly important to ensure construct validity so that meaningful conclusions can be drawn from the simulation results. The following subsections provide brief descriptions of each Staged World and the contributing perspectives gain from those experiences that influenced my Spartan Laboratory simulation environment.

*Pavilion Lake Research Program (PLRP)*

The Pavilion Lake Research Program (PLRP) is a unique field analog environment because it provides a real (non-simulated) multi-disciplinary, science and exploration endeavor that

Table 5.1: NASA analog research programs that were leveraged as Staged Worlds to support the envisioning process of the EVA work domain.

| | Pavilion Lake Research Project (PLRP) | NASA Extreme Environment Mission Operations Project (NEEMO) | | Biologic Analog Science Associated with Lava Terrains (BASALT) | |
|---|---|---|---|---|---|
| Deployment Name | PLRP-3 | N20 | N21* | BASALT-1 | BASALT-2 |
| Deployment Date | June 2015 | July 2016 | July 2017 | June 2016 | November 2016 |
| # of EVAs | 10 | 10 | 10 | 10 | 10 |
| Avg. EVA duration | ~90 min | ~4 hours | ~4 hours | ~4.5 hours | ~4.5 hours |
| Simulated Gravity Environment | Micro-gravity | ~Mars Surface gravity | | Mars-Surface (1-g) | |
| Time Delay | 5 min | 5 & 10 min | 15 min | 5 &15 min | 5 &15 min |
| EVA Objectives | Science-driven; biological characterization of microbial life | Science & pioneering objectives; astrobiology and geology goals combined with engineering and construction objectives | | Science-driven; biological and geological characterization of mars analogue terrain | |
| References | Miller *et al.*, 2016 | Chappell *et al.*, 2016, Chappell *et al.*, 2017, Miller *et al.*, 2017 | | Beaton *et al.*, 2017, Deans *et al.*, 2017, Miller *et al.*, 2017 | |
| Cumulative EVA Time | ~15 hours | ~80 hours | | ~80 hours | |

*I was not physically present in the field for EVA operations, but did participate in the design and evaluation of the EVAs remotely

focuses on understanding the morphogenesis of modern microbialites in Pavilion Lake, B.C., Canada within human spaceflight operational concepts (Lim et al., 2011). Conducting science at Pavilion Lake requires working underwater and the PLRP team has used a variety of technologies to map and sample the full breadth (lake length = 5.8 km) and depth (max depth = 65 m) of Pavilion Lake (Lim et al., 2010, 2011). I participated in the final PLRP deployment in June 2015 which included the use of Remotely Operated Vehicles (ROVs) and SCUBA diving to gather science data that met the specific research objectives. I was the EVA Exploration Operations Lead who was responsible for developing the EVA timelines to be utilized each day to meet the particular priority science objectives of the deployment. The concept of operations leveraged previous PLRP and other NASA analog structure that consisted of human and robotic assets who were supported by a mission support team located on shore. Figure 5.3 shows the concept of operations and key operations of the EVA team. I participated as the IV1 operator and Capsule Communicator (CAPCOM) positions throughout the deployment. Through this involvement,I tracked EV crew progress throughout each EVA execution and facilitated exchange of information between the EV crew and the supporting science personnel located in Mission Control.

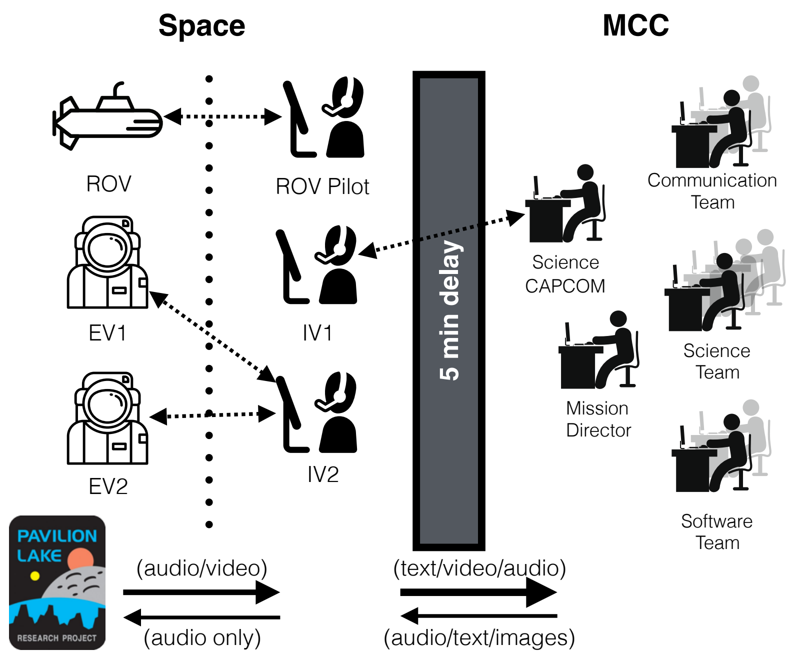



Figure 5.3: PLRP June 2015 deployment concept of operations.

A complete description of the June 2015 PLRP deployment can be found in Miller et al. (2016b). Here I highlight only a few key perspectives that shaped my Spartan Laboratory development efforts.

1. Science objectives will have profound implications to future EVA operations. As shown in the EVA work domain AH, EVA objectives have significant influence over nearly all aspects of EVA operations. No only will EV tasks change, but the demands on information flow, expectations and influence from support personnel will be added to existing EVA operations.

2. PLRP continually demonstrated evidence of hypothesis-driven timeline design and restructuring that I found to be in stark contrast to the timeline design efforts currently exhibited in the current work domain. Present-day EVA timelines, given their engineering objectives, are typically well scripted and known in advance and significant 'last-minute' changes to EVA timelines require extensive assessments to ensure crew and vehicle safety. Coping with the rapid shifts in science priorities will impose significant demands on EVA equipment and personnel to meet these demands.

3. In terms of the IV operator, consensus assessments indicated that a separation of responsibilities between two IV operators could be beneficial. As shown in Figure

5.3, IV1 managed the science conversation across time-delay with the science team while IV2 communicated with and directed the EV crew.

4. PLRP inspired a few new metrics to quantify EVA execution progress: Timeline Margin and Minutes Behind as described in Chapter 4.

PLRP provided a first-hand account of the new sources of variability that could result from attempting to achieve science objectives during EVA. The success of one EVA directly impacts the remainder of the planned EVAs in the mission. Overcoming the challenges associated with this perspective is outside the scope of what I could reasonably hope to accomplish in my Spartan Laboratory setting. The cumulative shifts and influence of completing successive scientifically driven EVAs is well beyond the scope of this study. However, during execution, maintaining some component of science objectives should be implemented within the EVA timeline for simulation. While the inclusion of scientific communication is likely in future missions, I also deemed that aspect outside the scope of my Spartan Laboratory. Therefore, I focused only on operations-related communication (e.g. system states and instructions) between a single IV operator and MCC.

*NASA Extreme Environment Mission Operations (NEEMO)*

The NASA Extreme Environment Mission Operations (NEEMO) Project is an analog environment located in an underwater habitat known as Aquarius located off the coast of Key Largo, Florida at a depth of 62 feet. Since 2001, NEEMO has simulated living in a spacecraft and test extravehicular activity (EVA) techniques and exploration concepts for future space missions for a variety deep-space destinations (e.g. asteroids, the Moons of Mars and Mars surface). I supported the NEEMO 19 and 20 missions as an EVA Exploration team member during the summer months of 2015 and 2016, respectively. These deployments in particular were the first time marine biology research objectives which served as a surrogate for planetary research objectives were integrated into EVA timelines. My responsibilities during these deployments involved assisting with the EVA timeline development process prior to the mission and the execution of EVA timelines throughout the missions.

During NEEMO 19, I served as both a Science CAPCOM and EVA operator who facilitated exchange of information between the science team, MCC and IV. Figure 5.4 shows the concept of operations involved during these deployments.

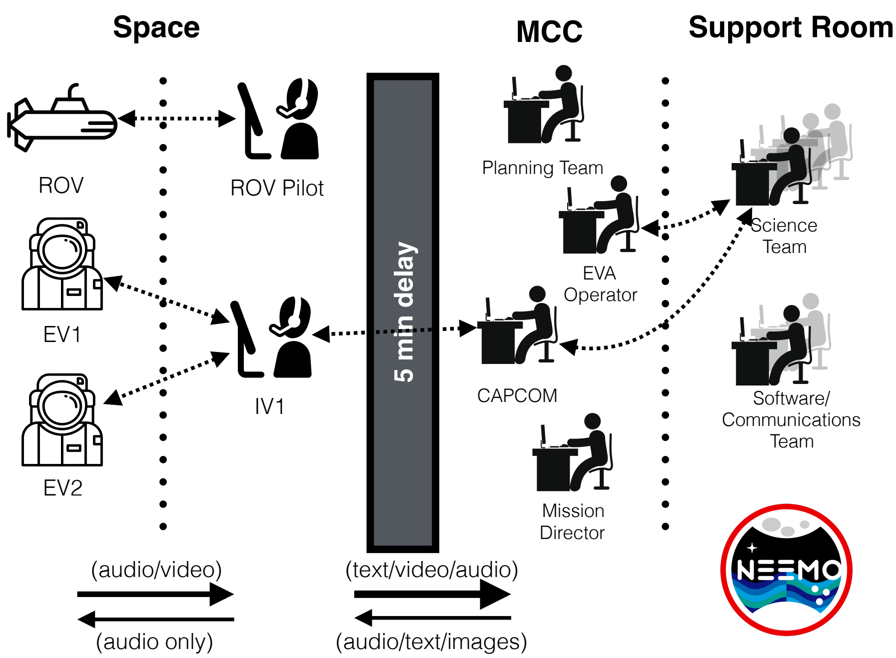



Figure 5.4: NEEMO 19 and 20 deployment concept of operations.

For NEEMO 20, my involvement focused solely on the design of the IV workstation. Figure 5.5 shows a representative set-up of the workstation configuration. I aided in the design of the IV workstation and supported survey data collection remotely during the mission.

A complete description of the NEEMO 20 and 21 deployments can be found in Chappell et al. (2016, 2017). Here I highlight only a few key perspectives that provided additional refinement to my Spartan Laboratory development efforts.

1. The information distribution amongst a larger flight team can be challenging to coordinate, particularly when the time-to-effect EV crew actions are tracked within a time-delayed environment. Tools that support this MCC-centric capability should be addressed but are outside the scope of my specific research agenda.

2. Accurate anticipation plays a critical role in exchanging the correct insight/instruction within the appropriate amount of time. The IV operator in particular plays an important role in helping MCC to anticipate timeline execution progress so that MCC can

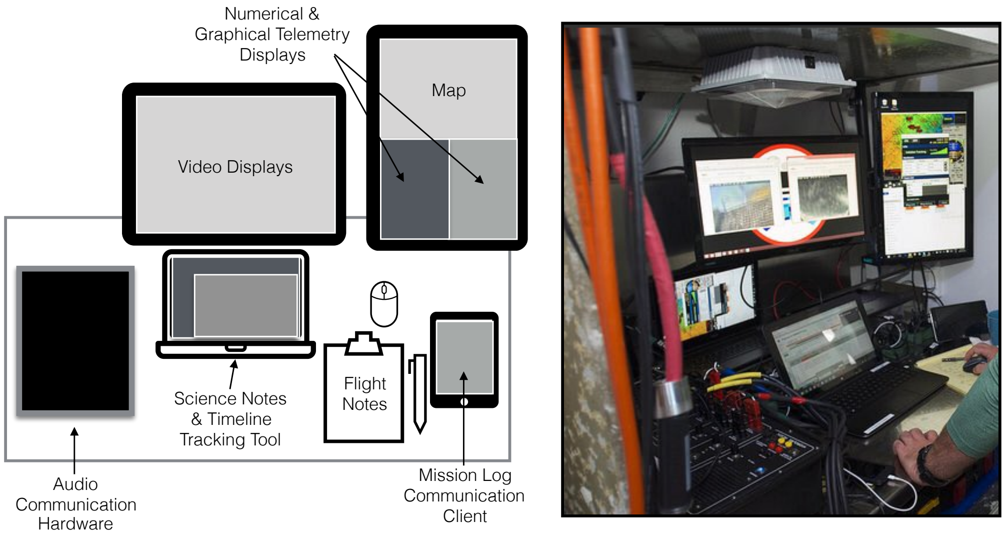



Figure 5.5: NEEMO 20 IV workstation configuration.

better predict what the crew will be doing in the near future. Therefore, an additional metric I found important to quantify in my Spartan Lab is how the specific communication patterns of the IV operator was throughout execution.(e.g. comprehensive coverage of all Timeline components and when everything was talked about - Proactive, retroactive etc.)

3. The IV workstation can quickly become cluttered with a number of information displays. Not only do those sources of information need more refinement, how each individual source is integration to yield effective IV support is an area of open research.

4. Operating robotic assets will add additional complexity to the IV workstation configuration. The NEEMO deployments leveraged an operator dedicated to controlling the ROV. The integration challenges that exist with these remote assets were deemed to also be outside the scope of my study. Additionally, video and geospatial location displays was purposefully excluded from my Spartan laboratory design.

The NEEMO deployments offered me the opportunity to see a larger integration concept of operations to perform future EVA missions. While my involved was dedicated primarily to MCC support, I also observed and obtained some preliminary user feedback from the IV operators using some of the same surveys I was in the process of generating for my Spartan Laboratory. This process helped me refine my survey materials used in my Spartan laboratory experiments.

*Biologic Analog Science Associated with Lava Terrains (BASALT)*

The Biologic Analog Science Associated with Lava Terrains (BASALT) project is a planetary analog program dedicated to the examination of microbial communities in terrestrial volcanic flows. BASALT focuses on the advancement of EVA exploration within the context of high-fidelity scientific objectives as a means to identify what exploration techniques and technologies will be necessary for future operations. This program involves a large team of specialists organized into various console positions to support EVA operations as shown in Figure 5.6. In addition to scientifically relevant objectives, BASALT applies mission constraints such as time-delayed communication and bandwidth restrictions as a means to explore and reveal what concepts of operations and technologies might be needed in future operations. Within this program, I participated as an EVA exploration team member who assisted in the design, development and execution of EVA in both the BASALT-1 and BASALT-2 deployments. During execution, I spent time observing IV operators as well as served as the Science Communicator (SCICOM) where I synthesized science team input to relay to the IV crew.

Additionally, I focused on the specific design considerations and data collection pertaining to the IV workstations for both deployments. Representative configurations from each deployment are shown in Figures 5.7 and 5.8. What is important to note here is variety of discrete sources of information that exist within the workstations and the variety of aspects these tools aims to support.

During BASALT-2, I also performed a pilot examination of the Advanced DSS software platform. EVAs were first tracked alongside actual operations using the Advanced DSS to ensure operational proficiency (See Figure 5.9). Once ready, the Advanced DSS prototype then was introduced as part of the IV workstation for use during execution and user feedback was obtained.

A more complete description of the BASALT-1 and 2 deployments can be found in Miller et al. (2017b); Beaton et al. (2017); Deans et al. (2017). Here I highlight only a few

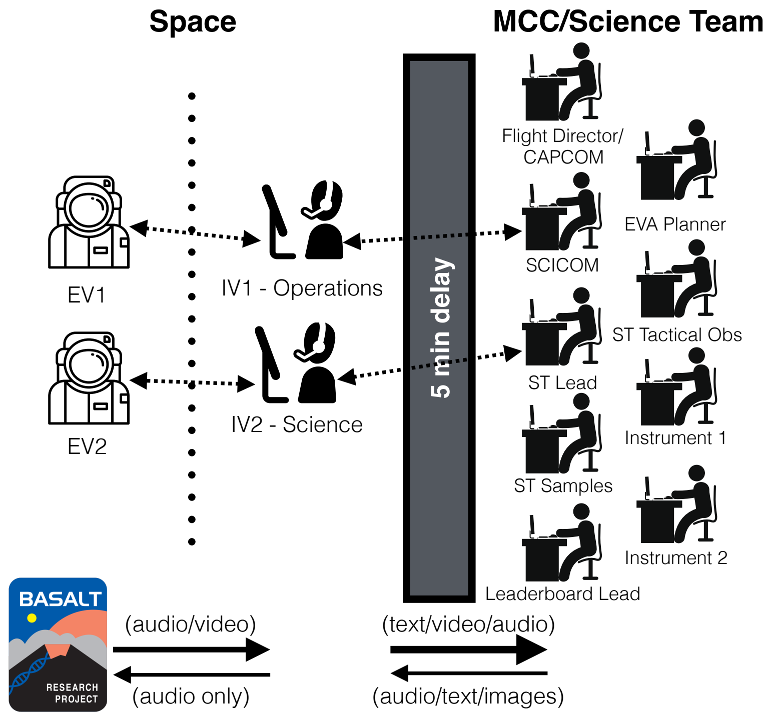



Figure 5.6: BASALT-2 deployment concept of operations.

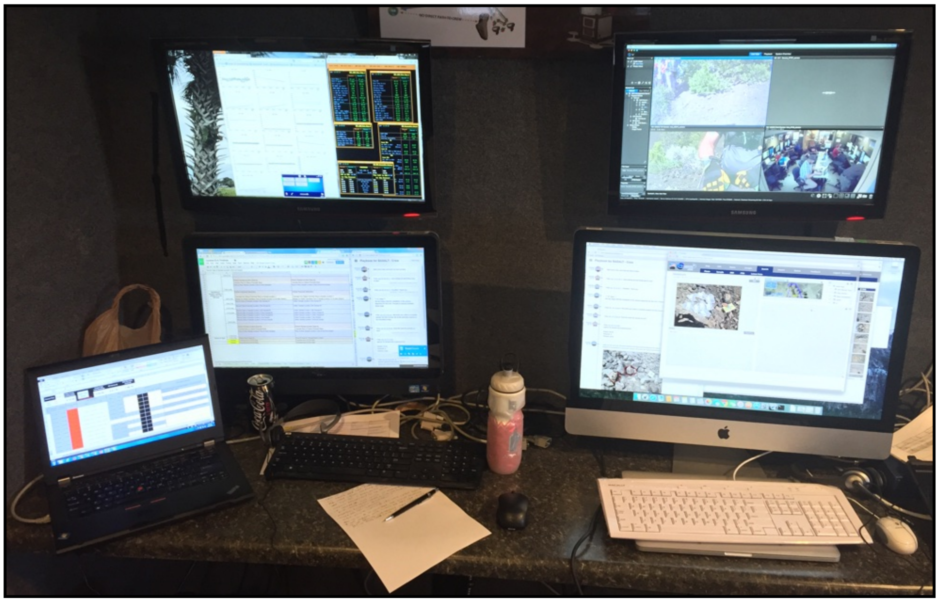
key insights that provided additional refinement to my Spartan Laboratory development efforts.

1. Terrestrial scientific field-work imposes a host of new demands on EVA operations both during and between EVA operations. Conversely, the EVA domain imposes new constraints on how scientific field-work is performed. Of particular note is the transplant of expert scientists who have spent their careers in the field themselves who now find themselves expected to perform similar work through a surrogate operators (e.g. EV crew members) all while sitting at a computer. There is a host of potential avenues to explore at intersections of these scientific field-work and EVA work domains, but remains outside the scope for my thesis.

2. Again, I observed the information distribution amongst a large flight team can be challenging to coordinate, particularly when the time-to-effect EV crew actions are tracked within a time-delayed environment. Tools that support this MCC-centric capability should be addressed but are outside the scope of my specific research agenda.

3. Performing EVA with two IV operators introduces an additional avenue for coordination challenges. The integration of specific actions such as recording, verifying and directing EV crew actions is an open area of continue research, but is again outside the scope of my work.

4. As found with the NEEMO analog, the IV workstation can quickly become cluttered with a number of information displays. Not only does those sources of information



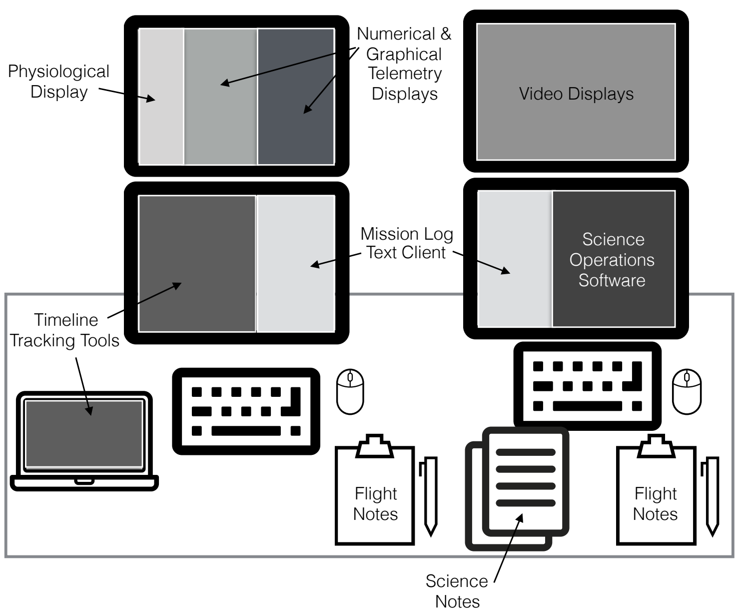



Figure 5.7: BASALT-1 IV workstation configuration.

need more refinement, how each individual source is integration to yield effective IV support is an area of needed research.

5. In terms of the Advanced DSS prototype testing, the prototype was refined throughout the mission and performed as expected. Only the Activity step level was tested and the timeline logic performed as expected.

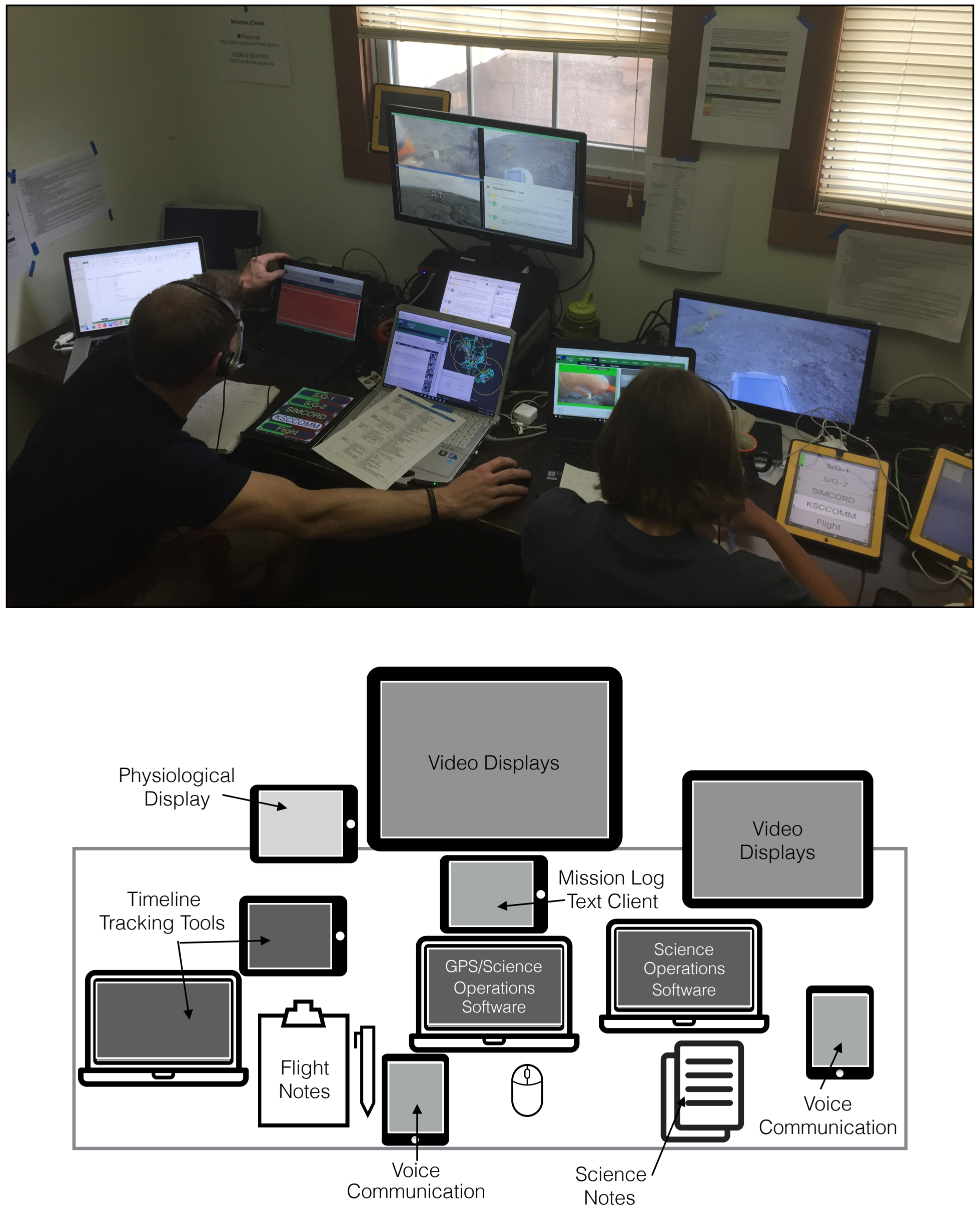



Figure 5.8: BASALT-2 IV workstation configuration.

The BASALT deployments provided me additional exposure to potential future concepts of operations. Additionally, I was able to directly observe IV operations in particular and pilot the Advanced DSS design within this operational environment to ensure the internal logic and DSS interactions were correct and desired prior to the Spartan laboratory experiment.

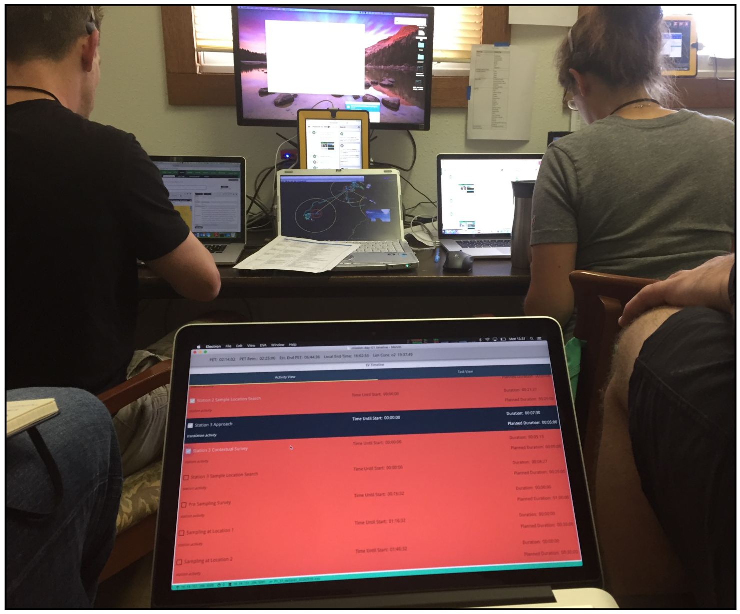


Figure 5.9: BASALT-2 Advanced DSS prototype testing.

### 5.1.3 Spartan Laboratory EVA Simulation Environment Construction

Table 5.2 shows a summary of the support system elements for both the Staged Worlds and Spartan Laboratory settings organized into five primary work functions. The Staged worlds attempted to incorporate more support systems elements that span not only existing EVA work functions but also include novel functions such as physiological and science data management, which is currently not under the purview of EVA flight controllers. My examination of the existing EVA domain, coupled with Staged World involvement, enabled me to target specific components of the domain to include in my Spartan Lab setting as shown in Table 5.2.

Additionally, I was able to scope the particular personnel roles and responsibilities within the Spartan Lab setting. Figure 5.10 shows the resultant Spartan Lab configuration with relevant agents and communication pathways. The IV operator was the study participant who was responsibility for fulfilling both timeline and life support system management functions within the communications environment shown in Figure 5.10. Timeline management involved providing task specific information to EV crew when needed to

Table 5.2: Staged World and Spartan Lab support system comparisons.

| | | Staged Worlds | | | |
|---|---|---|---|---|---|
| Work Function | Support System Elements | NEEMO-21 | BASALT-1 | BASALT-2 | **Spartan Lab** |
| Timeline Management | Summary Timeline | ✓ | ✓ | ✓ | ✓ |
| | Detailed Procedures | ✓ | ✓ | ✓ | ✓ |
| | Flight Notepad | ✓ | ✓ | ✓ | ✓ |
| | Map/Geospatial Tracking Display | ✓ | ✓ | ✓ | ⊗ |
| Life Support System Management | Numerical Telemetry Display | ✓ | ✓ | ⊗ | ✓ |
| | Graphical Telemetry Display | ✓ | ✓ | ⊗ | ✓ |
| Communication Management | Video | ✓ | ✓ | ✓ | ⊗ |
| | Audio | ✓ | ✓ | ✓ | ✓ |
| | Text Client | ✓ | ✓ | ✓ | ✓ |
| Physiological Management | Physiological Data Display | ⊗ | ✓ | ✓ | ⊗ |
| Science Operations Management | Science Data Display | ⊗ | ✓ | ✓ | ⊗ |
| | Science Notepad | ✓ | ✓ | ✓ | ⊗ |

[a]Shaded items indicate items not included or actively managed by present-day ISS IV operators. In particular, the physio- logical management work function currently resides with Flight Surgeon located within Mission control, and Science Operations Management only existed during the Apollo Program.

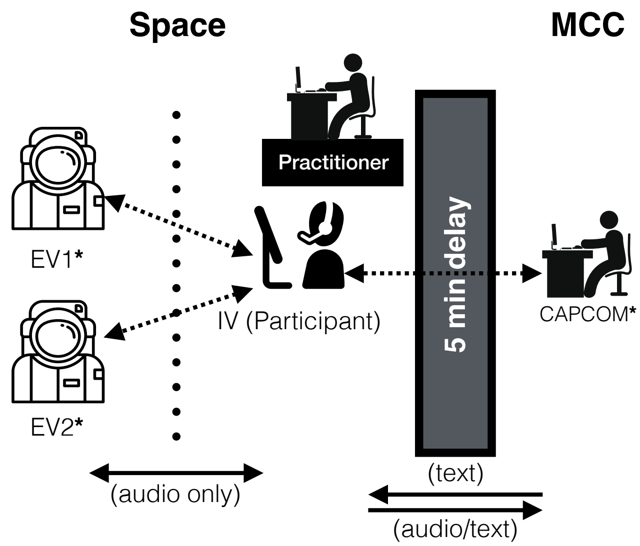



Figure 5.10: Spartan Lab concept of operations (* indicates surrogate personnel).

support task execution, verifying task procedures were performed correctly, and assessing timeline execution progress. Life Support System Management involved tracking telemetry system dropouts and consumable values and identifying life support system anomalies (e.g. trend events). Additionally, the IV operator was responsible for integrating timeline progress with life support system consumable estimates to calculate an estimate of Minutes Ahead/Behind and overall Timeline Margin. Finally, these responsibilities were fulfilled while maintaining audio communication with the EV crew and time-delayed text conversations with MCC. Types of communications included answering EV and MCC questions, providing task-relevant details to EV and MCC, and acknowledging receipt of MCC input.

Each EV crewmember was dedicated to particular types of activities that might be performed in future operations. EV1 performed the role of crew commander (CDR) who also served as the engineering specialist. As commander, EV1 tasks involved deploying and activating Mars Resource Units (MRU) which contained scientific experimental packages (similar to packages deployed during Apollo and NEEMO EVAs). The EV1 timeline design resembled engineering focused actions that were executed in a linear sequence of events. EV2 played the role of a Mars Mobile Pilot (MMP) who was rover pilot and crew geologist. EV2 timeline tasks included collecting scientific samples, taking picture of interesting geological features, providing contextual observations of the worksites and piloting the rover. EV2 timeline design resembled the station exploration elements of Apollo timelines as well as the science exploration actions performed during NEEMO and BASALT analogs. In effect, the EV2 timeline was more loosely structured and involved the iterative completion of Tasks and Subtasks in contrast the linear sequence of events performed by EV1. I was situated within the Spartan Lab setting as the Practitioner who was a silent observer during simulations. I facilitated all training exercises and post-experiment survey data collection and ensured the software and surrogate EV astronauts maintains simulation fidelity and recorded observational notes about how the IV operator performed throughout the simulations. MCC was performed by EV1 who sent scripted messages via the text client at specific times during each simulation.

*Implications for Simulation Environment Development*

Appropriately scoping the envisioned world is a challenging, yet necessary component of the overall design process. Instead of artificially creating a laboratory setting myself, I embedded myself within larger Staged World research programs to calibrate what components I should and should not include in my Spartan laboratory setting. This is important for a number of reasons: 1) the scale and scope of the simulation environment can have a direct impact on the ability to make conclusive statements about system designs, 2) the overhead in planning, resources and cost of envisioned worlds can become prohibitive, 3) research objectives can bias the development of the envisioned world, and 4) design solutions might be verified to meet particular specifications, however validation plays an important role in knowing whether the solutions actually meet the user's needs.

The spartan laboratory provided a targeted setting for my prototype design solutions to be more closely examined. It is important to note that the goal of the spartan laboratory should not be to explore too many dimensions of the work at once, but rather identify what specific work aspects are worth investigating in the first place. My research efforts were aimed at envisioning what future software support systems will be needed for future EVA operations. Therefore, I built a simulation environment within which to test a baseline and advanced support system to examine the utility of each within hypothesized future EVA operations. Below are a few key aspects of the construction effort that considered to ensure my simulation environment was appropriate:

- The aim of this field work was to answer: what might be contained in the envisioned world and what was important enough to simulate/emulate?

- Another important component I had to consider was appropriately simulating the natural variability exhibited during operations. Crew timeline execution can vary both in terms of time and tasks performed (As discussed in Chapter 4). Becoming familiar with that tempo in a Staged World and comparing that to my Natural World investigation provided the exposure necessary to shape my spartan lab scenarios.

- The nature of timeline and life support system synthesis currently resides in two separate MCC support teams. How might the unification of these two work functions become a reality in our spartan laboratory? Therefore, my spartan lab focused on the 'moment-by-moment' synthesis of timeline execution and life support system monitoring to explore how we might enable the integrated support of these two inherent EVA work functions.

- Given the lack of formal work domain definition of Mars surface operations, I assumed that utilizing novice EVA personnel provided the opportunity to examine the limits of crew performance within the spartan lab. Training considerations and learning effects for both the surrogates/practitioner as well as the participants must be accommodated in the data collection and simulation execution process. The more targeted the research objectives of the Spartan Lab, the more targets the training could be to get capable participants 'up-to-speed' quickly.

- The construction of the simulation elements, both hardware, paper products, and software takes careful planning and significant effort. I replicated many of the existing EVA artifacts first in the form of the Baseline system. Then, I focused my attention of novel design solutions so that I was not trying to balance both novel work domain design and prototype designs in the same experiment. Instead, I divided the Spartan Lab into what would be included if we were to directly reorganize the existing domain, and then within that reorganization, examine how novel software systems might promote sufficient support.

- The measures and metrics by which to quantify the performance within the Spartan Lab must be defined. This process involves measuring variables that have work domain implications (e.g. Minutes Behind and Timeline Margin).

In summary, the staged world provided me an opportunity for practitioners to gain operational experience within the future context, without contending with the volume of details necessary to describe the work domain context. This observational opportunity enabled me to contrast the existing domain and what the future might entail, and helped identify areas for more targeted research objectives to be examined in a more controlled setting, known as the spartan laboratory. The remainder of this Chapter describes the Spartan Lab setting and experimental procedures employed to conduct my simulation.

## 5.2 Spartan Laboratory Experiment Description & Method

A controlled experiment examined the effectiveness two different DSS prototype designs in envisioned EVA operations scenarios. While using the different prototype designs, IV operator proficiency, performance and overall level of cognitive support were assessed. The following section describes the simulation details, materials, metrics and measures used in the experiment.

### 5.2.1 Participants

Twelve engineering doctoral candidates participated in this experiment. All participants had no prior experience or qualifications supporting EVA operations. The selection criteria for their involvement included (1) good academic standing and (2) successful completion their academic qualification examination for their respective doctoral program, (3) were not colorblind, and (4) fluent in English. Participant ages varied from 25 to 31 with an average age of 27.2 $\pm 1.9$ years. This population was deemed representative of surrogate astronauts both in age and their demonstrated scholastic aptitude.

Prorated compensation up to $200 was provided if all 4 sessions were completed. Participants were compensated $40 for the initial training session, $45 for the 2nd experimental testing session, $55 for the 3rd retraining session session and $60 for the 4th and final experimental testing session. All participants completed all four sessions. Only one participant withdrew from the first session due to personal reasons. The IRB protocol can be found in Appendix A.5.

This experiment consisted of a research team comprised of myself and a team of eight graduate/undergraduate researchers who served as support staff to conduct the simulations as surrogate astronauts/MCC personnel. Each staff member was an engineering major with an interest in human spaceflight. They participated in orientation training sessions to introduce support team to the simulation facility and materials and were trained to conduct their specific simulation responsibilities as a surrogate astronaut as described in the remainder of this chapter.

### 5.2.2 Experimental Design

The experimental design was a cross-over design with each subject evaluating both DSS prototypes across all run scenarios. Table 5.3 shows the design of experiments. All participants completed a training and orientation session which concluded with a certification run prior to performing separate experimental sessions to ensure adequate proficiency. The two main independent variables, DSS configuration and Scenario, were counterbalanced to account for learning effects. Scenarios consisted of three different timeline execution scenarios where the EV crew were either performing a nominal (Nom) timeline, or executing the timeline ahead (Ah) or behind (Be) schedule. All certification runs were nominal timeline execution scenarios. In total, 8 scenarios were developed for this study and each participant performed cumulatively 2 hours and 20 minutes of simulated Mars surface EVA operations divided into 4 separate sessions. Over 400 human-hours of personnel time was required to conduct this study with an average of $\approx 13$ hours of simulation time spent with each participant.

Table 5.3: HITL experimental design.

| | Baseline DSS | | | | Advanced DSS | | | |
|---|---|---|---|---|---|---|---|---|
| **Participant #** | **Cert** | **Run 1** | **Run 2** | **Run 3** | **Cert** | **Run 4** | **Run 5** | **Run 6** |
| 1 | A | Ah | Be | Nom | B | Nom | Ah | Be |
| 2 | A | Be | Nom | Ah | B | Ah | Nom | Be |
| 3 | A | Nom | Ah | Be | B | Ah | Be | Nom |
| 4 | A | Be | Ah | Nom | B | Nom | Be | Ah |
| 5 | A | Be | Nom | Ah | B | Ah | Nom | Be |
| 6 | A | Nom | Be | Ah | B | Be | Ah | Nom |
| | **Advanced DSS** | | | | **Baseline DSS** | | | |
| 7 | B | Be | Ah | Nom | A | Nom | Be | Ah |
| 8 | B | Ah | Nom | Be | A | Be | Nom | Ah |
| 9 | B | Nom | Be | Ah | A | Be | Ah | Nom |
| 10 | B | Ah | Be | Nom | A | Nom | Ah | Be |
| 11 | B | Ah | Nom | Be | A | Be | Nom | Ah |
| 12 | B | Nom | Ah | Be | A | Ah | Be | Nom |

*Independent Variables*

The experimental design had 2 factors (DSS configuration and Scenario) each with 2 and 3 levels, respectively (Configuration: baseline vs. advanced and Scenario: nominal vs. ahead vs. behind) arranged as a counterbalanced repeated-measures design. Maintaining a within-subjects design enabled the quantification of individual differences by comparing the scores of a subject in one condition to the scores of the same subject in other conditions. As a result, each subject serves as his or her own control, which is particularly important given the small sample size in this study. In effect, within-subjects design provided considerably more power than between-subjects designs and more opportunity to detect an effect of the independent variables. Table 5.3 shows the full experimental design, decomposed by subject, DSS configuration, and run order. In total 36 testing runs were performed under each DSS configuration (72 runs in total). Prior to each testing session, a training and certification simulation session was completed. Each participant was trained and certified for each DSS configuration prior to conducting any simulation sessions which were performed on a different day. Each scenario type was completed 24 times (12 times for each DSS configuration).

This simulation operated at the lower limit of participants due to the lengthy experimental duration required (up to 16 hours of participant time - up to 4 hours each session). The objective of this simulation was to not only objectively measure performance differences between the two DSS configurations, but also explore what behavioral effects the simulation itself had on the participants. This study design is the first-of-a-kind representation of the minimum task expectations of IV operators in a simulated Mars scenario, therefore we want to explore and understand the deficiencies that exist in performing this subset of tasks, given the two DSS configurations. Future crew will undoubtedly be expected to perform even more work therefore, but we need a firm starting point that puts us on the pathway towards incorporating that complexity.

Scenario Description

Each scenario was derived from a combination of sources. During my Natural History study, I analyzed all Apollo Lunar surface EVAs to calculate the temporal evolution of how closely Apollo EV crew followed their nominal timeline (as indicated by the horizontal reference line). A nominal execution in this situation implies that the crew performed each action specified in their timeline at the exact moment scripted in their planned timeline. The temporal evolution of that deviation from nominal, quantified as 'Minutes Behind', is shown in Figure 5.11 for EVAs performed during Apollo 15, 16, and 17. The magnitude of Minutes Behind directly map to the resultant three scenario types (Nominal, Ahead, and Behind) used in the experiment. To reduce the chance of bias and anticipation, the scenarios between the two DSS configurations were offset by a few minutes so that unique, yet comparable in magnitude, answers existed for each scenario and DSS factor. The overall intent here was to replicate realistic magnitudes of timeline execution performance crew may perform on future missions by leveraging this historical precedence.

Additionally, the scenarios were designed to simulate *subtle and gradual* changes in timeline execution performance so that the experiment could quantify the lowest resolution

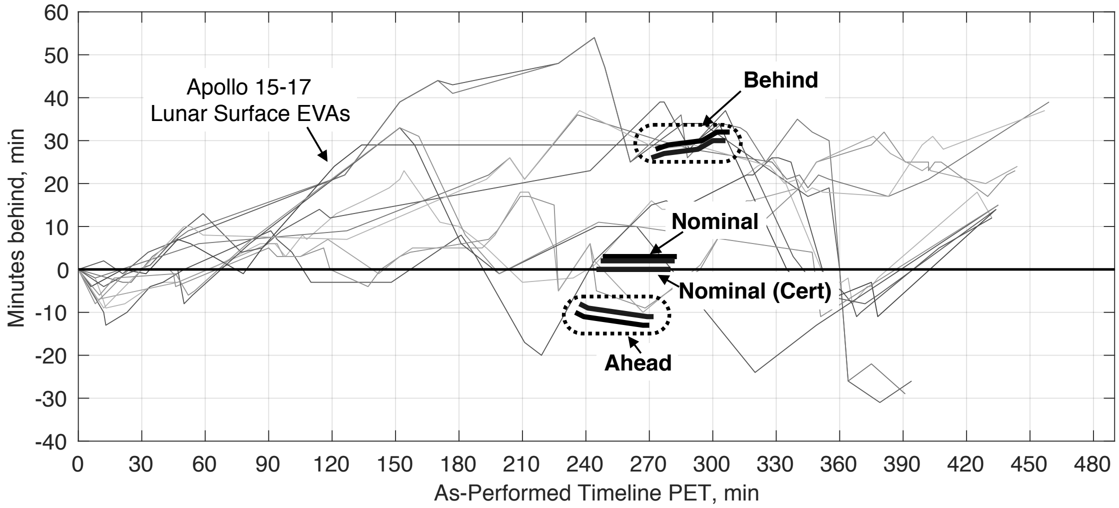



Figure 5.11: Experimental Scenarios derived from Apollo 15-17 Lunar Surface EVAs, see Miller et al. (2017a) for more details.

of timeline tracking capabilities the IV could demonstrate. This approach is in contrast to simulating larger, more sudden deviations and anomalies. The aim here is to scrutinize what nominal operations may look like and testing for how well an IV operator can be expected to perform under these expected nominal operations.

*Dependent Variables*

There is no single performance variable that can appropriately quantify overall IV operator performance or DSS effectiveness. Therefore, a variety of quantitative and subjective dependent variables related to important EVA domain-specific values was recorded as shown in Table 5.4. Each set of quantitative variable map to the specific work functions accounted for in the DSS designs into the simulation scenario. Subjective assessments were implemented to obtain targeted user feedback for each test condition.

Life Support System Management Variables

Telemetry tracking involved identifying both numeric and graphic trend events. Collectively, these domain specific metrics were recorded to quantify the level one situation awareness the IV operator maintained throughout each simulation run.

- **Numeric/Alert Event Recognition:** Numeric or Alert events corresponded to sig-

Table 5.4: HITL simulation dependent variables.

| Type | Work Function | Variable |
|---|---|---|
| Quantitative | Life Support System Management | Numeric/Alert Event Recognition |
| | | Trend Event Recognition |
| | | Trend Event Response Time |
| | Timeline Management | Step Coverage |
| | | IV Communication Behavior |
| | | Timeline Margin Calculation |
| | | Minutes Behind Calculation |
| | | Confidence Estimate |
| | | Time to Complete Margin Calculation ($TTC_{Margin}$) |
| | | Time to Complete Minutes Behind Calculation ($TTC_{MinB}$) |
| | Communication Management | IV to MCC Diaglog |
| Subjective | *Overall DSS Prototype Assessments* | Operator Proficiency Rating |
| | | NASA Task Load Index (TLX) |
| | | Cogntive Support Assessment |
| | | Interaction Assessment |

nal 'drop-outs' that occurred throughout execution on the numeric console displays. These events would trigger and remain on the display for 20 seconds at which point would disappear. The hit/miss counts for each event were recorded.

- **Trend Event Recognition:** Trend events corresponded to signal 'anomalies' that occurred throughout execution on the graphical displays. These events would appear on the graph as a deviation from the nominal trend data already shown on the screen (e.g. step change or slope change). The hit/miss counts for each event were recorded for each experimental run. Any additional trend events recorded by the IV operator beyond the scripted events were classified as surplus counts.

- **Trend Event Response Time:** For each trend event that was identified, the response time was recorded for each event.

Timeline Management Variables

Collectively, these variables were recorded to quantify the IV operators ability to provide adequate timeline support throughout EVA execution. level one situation awareness the IV operator maintained throughout each simulation run.

- **Step Coverage:** Based on IV/EV conversation, the timeline steps within each Station Activity were recorded for completeness. This variable correlates timeline verification responsibilities by measuring the extent to which (e.g. coverage) the timeline that was actually discussed throughout execution. Audio communication was the only means to communicate between EV and IV operators, therefore all step verification was required to be transmitted via audio.

- **IV Communication Behavior:** In addition to quantifying timeline coverage, tendencies in communication behavior was quantified. Each step was divided into four categories: Proactive / On-Time / Retroactive / Missed. As the names suggest, the IV conversation with IV was categorized based on when each individual step was discussed.

- **Timeline Margin Calculation:** At predetermined points throughout the simulation, the IV operator performed a timeline margin calculation. The process for calculating timeline margin is shown in Figures 4.11 and 4.26 respectively for each DSS configuration.

- **Minutes Behind Calculation:** Similarly at predetermined points throughout the simulation, the IV operator performed a minutes behind calculation. The process for calculating minutes is shown on Figures 4.11 and 4.26 respectively for each DSS configuration.

- **Confidence Estimate:** Upon completion of each timeline margin calculation, the IV operator provided a quantified over/under estimate to account for error they believed their answer may contain.

- **Time to Complete Margin Calculation ($TTC_{Margin}$):** The time to perform each timeline margin calculation was recorded throughout EVA execution.

- **Time to Complete Minutes Behind Calculation ($TTC_{MinB}$):** The time to perform each minutes behind calculation was recorded throughout EVA execution.

<u>Communication Management Variables</u>

- **IV to MCC Prompt Response Time:** Each message received from MCC was required to be 'acknowledged' by the IV operator. The time it took the IV to acknowledge each MCC prompt was recorded.

<u>Subjective Assessments</u>

- **Operator Proficiency Rating:** Operator proficiency was evaluated using an existing flight controller proficiency scorecard used during the certification process of ISS flight controllers. A subset of the scorecard that remained relevant for our simulation purposes was implemented. Six dimensions of proficiency were examined which included: Mission Cognizance, Systems Knowledge, Problem Recognition and Resolution, Console Management, Communication, and Attitude and Effort. See the Appendix XX for the full assessment sheet. Each EV crew member and myself individually completed this assessment for both the CERT and Run1 runs for each subject to quantify their training and testing session proficiency. In total, each participant was assessed on their proficiency by three to five separate people, depending on the EV crew session assignments. I scored every subject for both the Cert and Nominal runs.

- **NASA Task Load Index (TLX):** At the end of each run, the participants assessed their workload using the NASA TLX sub-scales as shown in Appendix A.5.
- **Cognitive Support Assessment:** At the end of each run, the participants assessed the cognitive support they received from their DSS configuration using a custom cognitive support assessment questionnaire. This questionnaire was adapted from a previous study that examined DSS designs in the health care domain. See Appendix A.5 for more details.
- **Interaction Assessment:** At the end of each training and testing session, the participants assessed their overall interactions with their DSS configuration using using modified Cooper-Harper scale assessment. This questionnaire was adapted from a previous study that examined unmanned aerial vehicle interface designs. See Appendix A.5 for more details.

### 5.2.3 Experiment Protocol and Control Mechanisms

At the initial meeting, participants provided written informed consent and were introduced to the goals of the study. Four sessions in total were completed by each participant. The time allocated within each session is summarized in Table 5.5. The maximum allowable time limit was 4 hours for any session, although only the first session tended to approach that limit. Most sessions lasted approximately 3 hours in duration.

During sessions 1 and 3, participants were provided a complete description of the study components and the environment within which they would be operating. A training power point presentation was completed with the researcher while sitting at the workstation to step through all components of the simulation environment and explain the purpose and expectations of each component. (Appendix A.5 contains the training materials and scripts implemented for additional detail.) Part-task simulation practice was performed where segments of a training timeline was performed for periods 5-7 minutes at a time. At the conclusion of each practice segment, the researcher highlighted and corrected any participant behavior deficiencies and answered any questions. This process of part-task practice was completed until the subject felt comfortable with all tasks expected of them and the practitioner was satisfied that they displayed the appropriate behaviors. Once practice was completed and all questions answered, the participant completed a full certification simu-

Table 5.5: HITL simulation session descriptions.

| Session | Time Allocation | |
|---|---|---|
| 1 | Orientation | 30 min |
| | Training | 2 hrs |
| | Break | 10 min |
| | Cert Sim | 50 min |
| 2 | Refresher | 30 min |
| | Run 1 | 50 min |
| | Run 2 | 50 min |
| | Run 3 | 50 min |
| | Post Sim Eval | 20 min |
| 3 | DSS Training | 2 hrs |
| | Cert Sim | 50 min |
| 4 | Refresher | 30 min |
| | Run 4 | 50 min |
| | Run 5 | 50 min |
| | Run 6 | 50 min |
| | Post Sim Eval | 20 min |

lation where the entire simulation was conducted from start to finish. The survey assessments were then completed and the session was concluded. These training sessions were performed for both DSS configurations. In total, each subject received an average of $\approx 2.5$ hours in the training sessions.

No two session for a single participant was performed on the same day to prevent burnout. Once a training session was completed, each participant returned for a testing session on that same DSS configuration. A brief refresher was performed prior to testing to remind participants of expected tasks and they were provided the opportunity to ask any final questions. Three independent testing runs were performed sequentially, with post-run survey questions and brief breaks provided between runs. Each (run + questionnaires) lasted approximately 50 minutes each in duration. Each test began with myself as the practitioner initializing the simulation by informing the subject of the current crew position in the timeline and the estimated minutes behind value for that test condition. In effect, I handed off the IV operator shift to the subject to start the simulation and initialize the specific scenario condition (e.g. nominal, ahead, or behind). For the duration of the simulation, I remained a silent observer of the subject and ensured all supporting testing infrastructure was stable. The EV crew, when specified by their scripts called "All Stop" over the communication system to trigger the end of the simulation, at which point I guided the subject to the subjective questionnaires to complete. During testing sessions, a brief break was offered between each scenario, before starting the next test.

In order to ensure a consistent simulation environment across all independent variables, a team of trained surrogate EV crew who followed strict scripted timelines was used. In total, eight personnel were trained as EV crew who role-played each EVA timeline as either EV1 or EV2 depending on their assignment for the session. Figure 5.12 shows an an image of the surrogate EV workstations and excerpt of the EV version of the EVA timeline to highlight. All red letter font indicate the times and instruction followed by the each EV crew. Every single step in the EVA timeline was scripted sequentially so that each moment of the simulation was assigned to each crew member.

The EV timelines also specified a minimum number of steps to vocalize during the simulation as a means to cope with instances of long periods silence from the IV operator. All other timeline related conversation generated from the EV crew was based on content first conveyed by the IV operator. For example, if the IV operator proactively conveyed that EV1 should deploy MRU C67, then the EV1 crew member would acknowledge and provide confirmation once they completed that step. Otherwise, the EV1 crew member proceeded to the next step without verbal confirmation. In effect, the more proactive and engaging the IV operator, the more readily EV crew provided awareness about their task progress. Furthermore, the IV operator only had the ability to inform the EV crew about timeline details, they could not force the EV tasks to go 'off-script.' EV crew statements also followed standard communication protocols by being short, concise statements using the push-to-talk audio system. EV crew were also allowed to talk to each other directly during the simulation while the IV operator only listened. Ad libbing to a certain extend

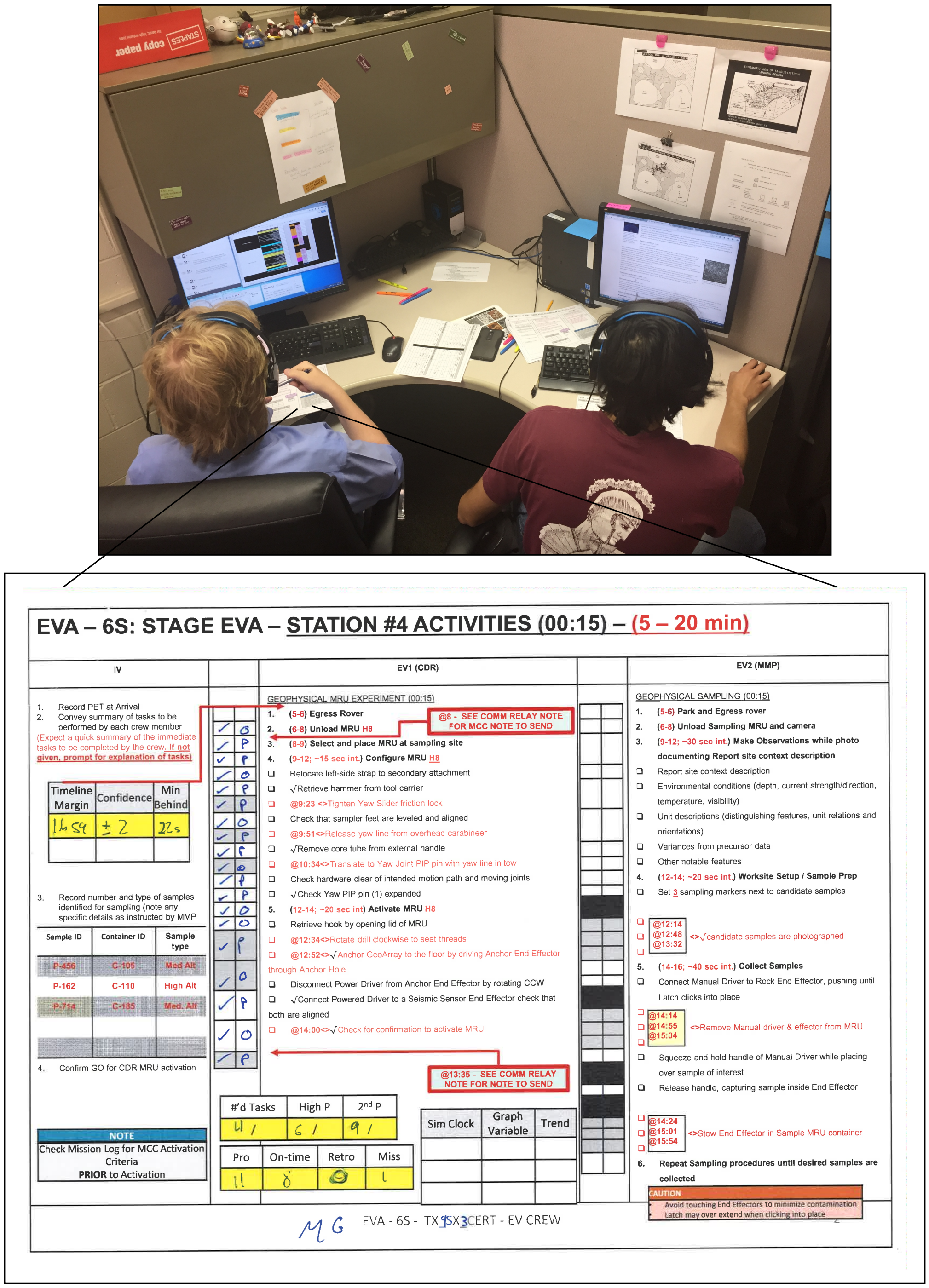



Figure 5.12: Surrogate EV crew workstation and EVA timeline excerpt.

was also allowed but was emphasized in particular areas of the timeline. During Translation activities the conversation was scripted to be more free-form allowing for general chatter to take place. Only the end of Translation was specifically scripted to end at a certain time. Station activities were regions of the timeline where each step in the timeline was tightly scripted to control for EV crew timeline execution progress. EV1 was responsible for sending the MCC text messages at specific times during the each run so that MCC messages appeared to the IV operator at specific times during execution. As a measure of consistency for EV crew performance, the difference in send times of MCC text messages between actual and scripted was recorded for each run.

### 5.2.4 Spartan Laboratory Objectives

The aim of the Spartan Lab simulations was to evaluate how well each prototype DSS design satisfies their specific design requirements in addition to compare and contrast each DSS design. Additionally, the Spartan Lab simulation provides an opportunity to demonstrate hypothesized design solutions and open the designs up to critique. The DSS prototypes are not meant to fully satisfy all the requirements identified in Chapter 4. Rather, the Spartan Lab serves to demonstrate how designs solutions might enable some of the key shifts that will need to occur within the future work domain (i.e. digitizing the EVA timeline, integrating system state understanding into the DSS designs, and re-imaging IV operator work flow.

# CHAPTER 6

# EXPERIMENT RESULTS AND DISCUSSION

As described in Chapter 5, the two designs presented in this work are my hypotheses for how to satisfy the requirements. To verify that these designs did meet the requirements and validate that the requirements (once met) facilitated the work needed, an evaluation of both designs was undertaken in a spartan simulation environment. The evaluation sought to answer the follow questions regarding the DSS prototype designs:

- Q1: How well and in what ways does <u>each</u> DSS prototype design satisfy their respective design requirements?
- Q2: Does the Advanced DSS more effectively support the IV operator during EVA operations? If so, in what ways? (e.g. How closely could the IV operator track EV crew timeline execution and telemetry data throughout EVA execution?)

Table 6.1 shows a summary of the dependent and independent variables utilized in this experiment. For a full description of each variable, see Section 5.2.2. Collectively, these domain specific dependent variables and various subjective DSS assessments were used to address Q1 and Q2 directly as discussed in Section 6.2.

To answers these questions, each data set was analyzed using linear mixed-effects regression, LMER, with the lme4 package in R (Bates et al., 2015). LMER enables the variance associated with random factors without data aggregation (Baayen et al., 2008; Judd et al., 2012). By using subjects as random effects, I was able to control for the influence of different mean ratings associated with each subject due to the crossed experimental design. Given the limited degrees of freedom available, no interaction terms were included in the mixed-models. Fixed effect factors incorporated into the LMER modeling included: DSS tool, Scenario, Scenario Order (to account for the ordering of scenario in which subjects were tested) , DSS order (to account for which DSS tool the subject first

Table 6.1: Independent and dependent variable summary.

| Independent Variables | Dependent Variables |
|---|---|
| **DSS Tool:** Baseline and Advanced | Numeric/Alert Event Recognition |
| **Scenario:** Nominal, Ahead, and Behind | Trend Event Recognition |
| **Other relavent factors** such as Scenario Order, DSS Order, Crew, etc. | Trend Event Response Time |
| | Step Coverage |
| | IV Communication Behavior |
| | Timeline Margin Calculation |
| | Minutes Behind Calculation |
| | Confidence Interval Estimate |
| | Time to Complete Margin Calculation ($TTC_{Margin}$) |
| | Time to Complete Min. Behind Calculation ($TTC_{MinB}$) |
| | IV to MCC Prompt Response Time |
| | Operator Proficiency Rating |
| | NASA Task Load Index (TLX) |
| | Cogntive Support Assessment |
| | Interaction Assessment |

used). Other factors such as probe type (which indicate specific periods during the simulation when Margin was estimated) and EV Crew (which distinguishes between EV1 and EV2) were also incorporated where appropriate. Opportunities to exclude non-significant fixed effects in the full LMER were explored by creating reduced order models and using ANOVA chi-squared testing to ensure the variance explained by the model was maintained. Additionally, residuals for each model were examined for normality assumptions. Unless otherwise noted, no violation of assumptions were found. Fixed effect significance was measured by performing an analysis of variance with Kenward-Roger approximation for degrees of freedom from the mixed-level models. Tukey post-hoc analysis with adjusted p-values using the Holm method were applied where appropriate. Significance and marginal significance levels were set to $\alpha = 0.05$ and $0.10$, respectively. For non-parametric data sets, non-parametric tests such as the Kruskal-Wallis and Pearson's Chi-squared tests were used as indicated. The Cert Scenario results are shown in most figures but was omitted from all statistical analyses.

## 6.1 Experiment Results

The results are divided into two main sections: Performance and Survey Assessments. The Performance Assessments results are arranged by Focus Area. First, the Timeline Management variables are examined and modeled. Secondly, the variables pertaining to the Life Support System Management focus area are discussed. Finally, the communication behavior data is examined. The Survey Assessment data first presents the operator proficiency ratings. Then the NASA TLX, Cognitive Support and Interaction assessments are presented. An integrated summary of results is presented in Section 6.1.3.

### 6.1.1 Performance Assessments

*Timeline Margin Calculation*

The timeline margin calculation was measured as an error between the IV operator estimate and a truth value. The closer to zero the error value, the more accurate or correct the answer. Positive error values indicated more conservative estimates and negative values are less conservative. The mixed-level modeling results are shown in Table 6.2 and discussed in detail below.

Table 6.2: Timeline margin error ANOVA results summary.

| Independent Variable | **Sum Sq** | Mean Sq | NumDF | DenDF | F.value | Pr(>F) | Significant Influence |
|---|---|---|---|---|---|---|---|
| **Tool** | 215.68 | 215.68 | 1.00 | 198.09 | 3.36 | 0.0684 | Marginally |
| **DSS Order** | 231.92 | 231.92 | 1.00 | 10.00 | 3.61 | 0.0866 | Marginally |
| **Scenario** | 531.77 | 265.88 | 2.00 | 198.09 | 4.14 | 0.0173 | Yes |
| **Scenario Order** | Omitted from model | | | | | | No |
| **Probe** | 1847.53 | 923.76 | 2.00 | 198.09 | 14.38 | 0.0000 | Yes |

Timeline Margin Error - DSS Tool, DSS Order, & Scenario

A Tukey Post-hoc analysis on DSS Tool revealed a marginally significant difference in Margin error ($p \leq 0.067$) with the Advanced Tool averaging 2 minutes (+)error compared

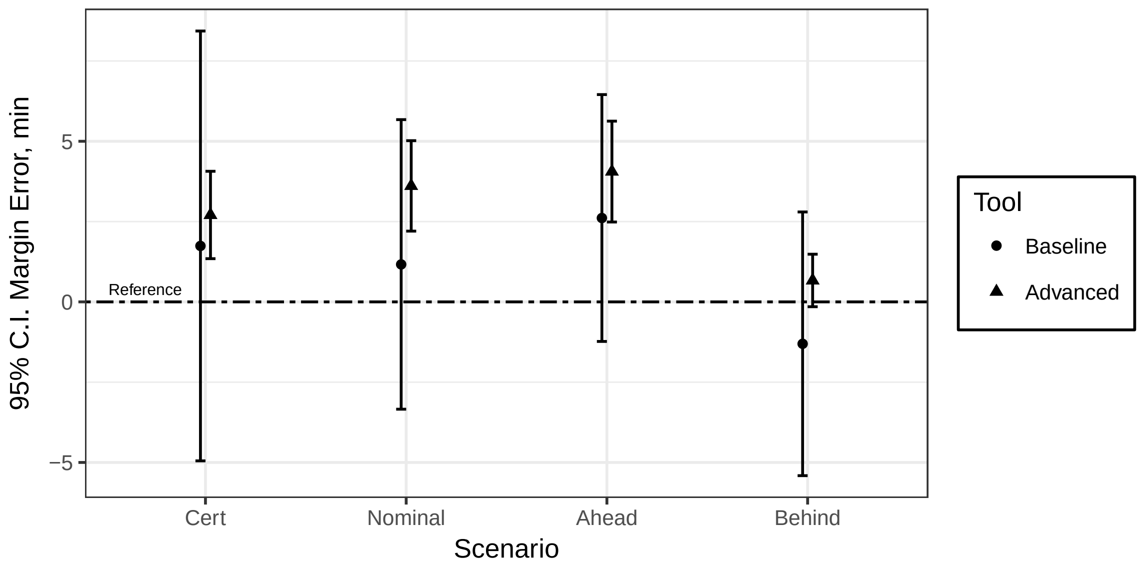



Figure 6.1: Timeline margin calculation error 95% confidence interval results per DSS and scenario.

the Baseline Tool. Positive error is conservative, and thus not inherently bad. A Tukey post-hoc analysis on Scenario revealed no statistical difference between Ahead and Nominal conditions. However, the Behind Scenario compared to Nominal and Ahead scenarios yielded marginal ($p \leq 0.085$) and significant ($p \leq 0.016$) differences, respectively. The order in which participants utilized each DSS tool had marginal significance on Margin error ($p \leq 0.057$), where those who utilized the Baseline Tool first tended to produce more positive (conservative) Margin estimates by ($\approx 2$ minutes) than those who were trained with the Advanced Tool first. This marginal impact of DSS Order might indicate a potential training effect in participants' ability to accurately compute the timeline Margin. Finally, as shown in Figure 6.1, all Advanced tool confidence intervals are more tightly bound as compared to the Baseline results. Outliers as large as -61 and +30 minute Margin errors were observed using the Baseline Tool. However, the mean Margin error values using the Baseline Tool tended to be more neutral in the Nominal and Ahead conditions than the Advanced which indicates there is a potential accuracy versus precision trade off between the two DSS designs under these conditions. The Behind scenario condition was observed to produce less conservative Margin errors under the Baseline Tool.

Timeline Margin Error - per probe

The Margin calculation was performed at three separate instances during each scenario simulation: the first time at the end of the first translation activity (tts4), the second time at the end of the second translation activity (tts5), and finally during the last station activity (s5end). The end of translation activity periods (tts4 and tts5) signified clear transition periods within the timeline and I hypothesized that performing the Margin calculation at these clear transition periods would be more accurate than in the middle of a Station activity where task progress can be more difficult to discern. Figure 6.2 and 6.3 shows the 95% C.I. Margin Error plots divided by the translation and station probes, respectively. A LMER using only tts response data indicated significant influence in DSS tool and probe type, only. The Advanced Margin error tended to be appropriately (+)3 minutes more conservative than Baseline estimates ($p \leq 0.0081$). Additionally, the calculations performed at tts5 tended to be (+)2.4 minutes larger than estimates calculated at tts4 ($p \leq 0.046$). For reference, tts5 occurred at approximately 20 minutes into the simulation whereas tts4 occurred approximately 5 minutes into each simulation scenario. This different in Margin error between the two tts probes might indicate a drifting tendency that occurs in Margin calculations as the timeline progresses (e.g. an accumulation of error). No statistical differences were observed between Scenario conditions for the tts probes.

Another model was constructed with only s5end Margin error data and significant influences by Scenario and DSS order were observed. The DSS Tool type did not have a statistically significant impact on s5end Margin error. A Tukey Post-hoc analysis revealed no statistical significance between s5end Margin error between the Ahead and Nominal conditions. However, Behind compared to Nominal ($p \leq 0.012$) and Ahead ($p \leq 0.0038$) showed significant differences, respectively. Finally, for the calculation of s5end, those participants who utilized the Baseline tool first averaged nearly (+)6 minutes more in their Margin estimate error as compared to those who utilized the Advanced tool first ($p \leq 0.018$). Again, those that were first trained on the Baseline tool may have experi-

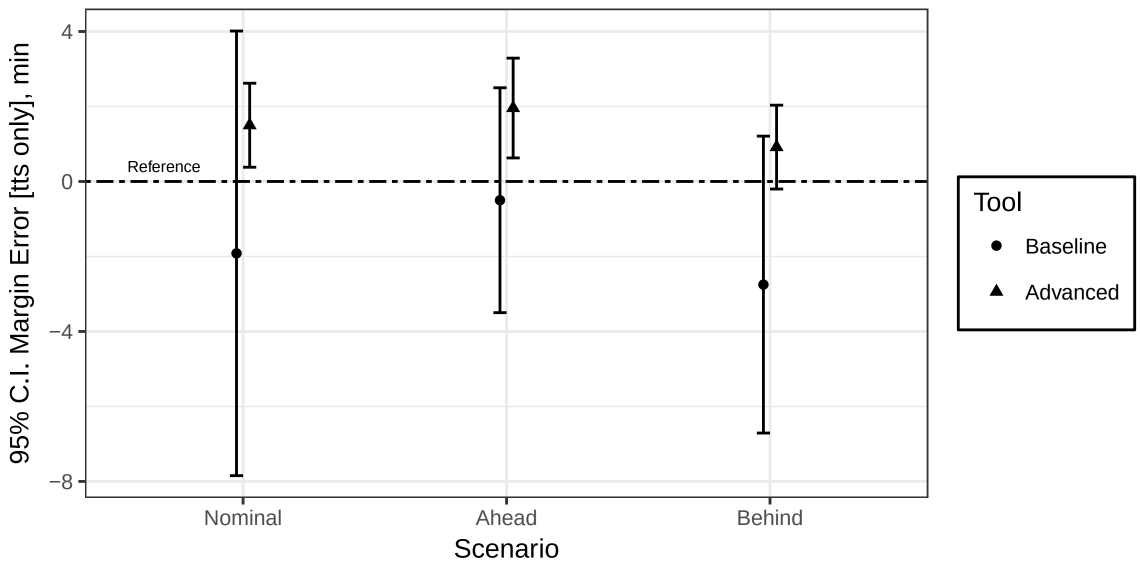



Figure 6.2: Timeline margin calculation error 95% confidence interval results per DSS and scenario for end of translation (tts4 and tts5) calculations only.

enced a more difficult learning curve as compared to those who first saw the Advanced Tool.

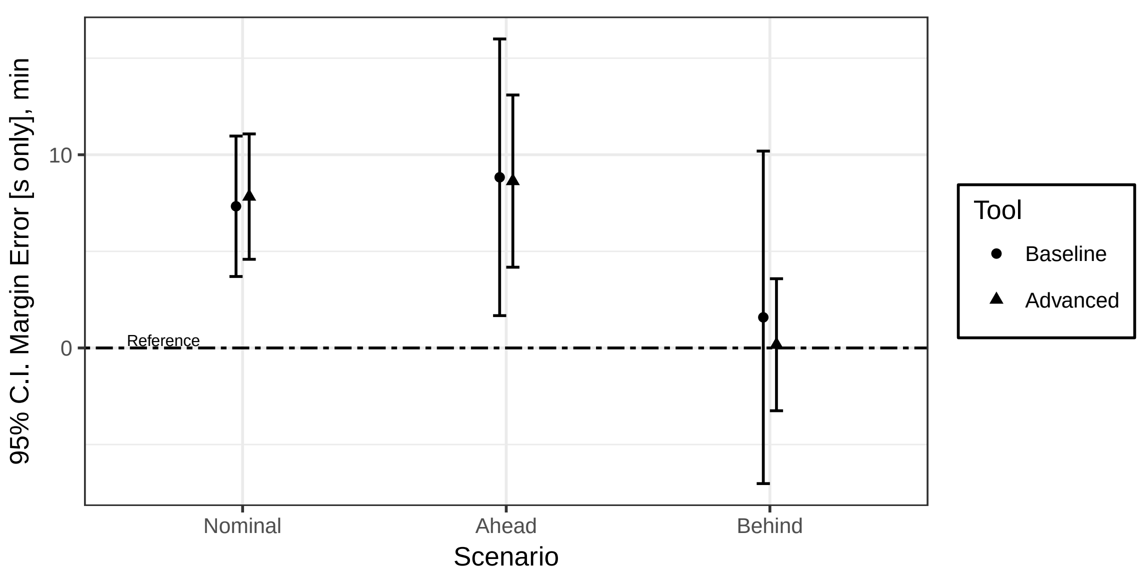



Figure 6.3: Timeline Margin calculation error 95% confidence interval results per DSS and scenario for station calculations only.

Finally, when we look across all scenarios, and investigate the temporal shifts in Margin error throughout the 35 minute simulations (e.g. perform first at tts4 ($\approx 5$ min), then at tts5 ($\approx$ 20 min), and then finally at s5 ($\approx$ 35 min)) we see a gradual growth in error as shown in Figure 6.4, particularly for the calculation performed within Station 5 activity. Marginal significance was observed between the tts4 and tt5 Margin errors ($p \leq 0.072$), and statistical significance was observed between s5end and tts4 (($p \leq 0.000$) and tts5 ($p \leq 0.001$). As shown in Figure 6.4, the magnitude of variability at the 95% C.I. level is managed to a much tighter degree using the Advanced tool ($\pm 2$ min.) over the Baseline ($\pm 5$ min.).

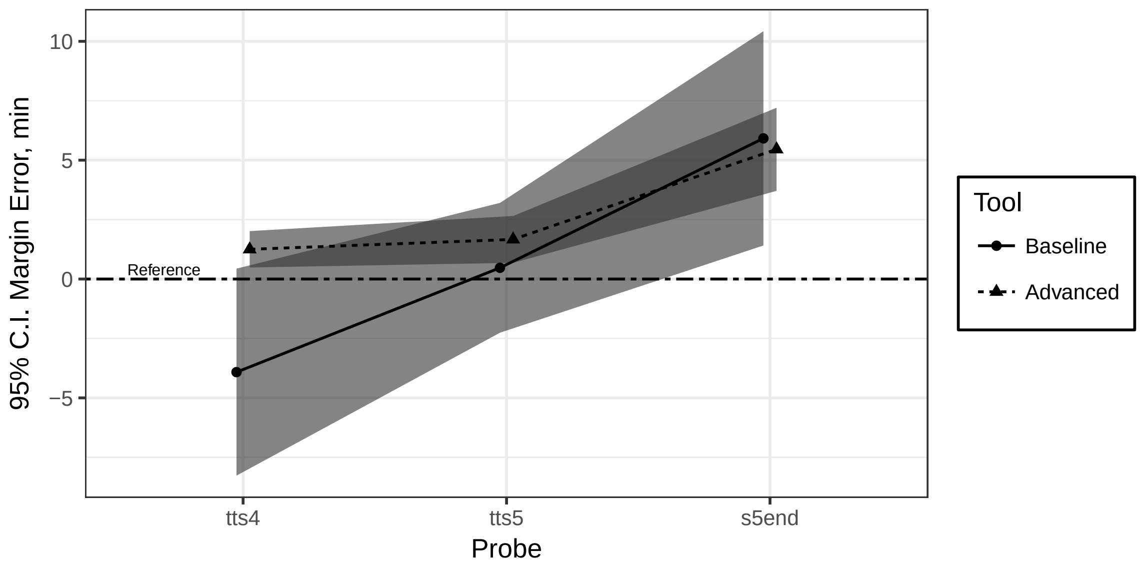



Figure 6.4: Timeline margin calculation error 95% confidence per specific probe across all scenarios.

*Minutes Behind Calculation*

The minutes behind calculation performance was also calculated as an error between the IV estimate and truth value. The closer to zero the error value, the more accurate or correct the answer. Positive error values are considered more conservative and negative values are less conservative. The mixed-level modeling results are shown in Table 6.3 and discussed in detail below.

<u>Minute Behind Error - Scenario and DSS Tool</u>

Table 6.3: Minute behind error ANOVA results summary.

| Independent Variable | Sum Sq | Mean Sq | NumDF | DenDF | F.value | Pr(>F) | Significant Influence |
|---|---|---|---|---|---|---|---|
| **Tool** | 481.26 | 481.26 | 1.00 | 326.00 | 33.93 | 0.0000 | Yes |
| **DSS Order** | 102.45 | 102.45 | 1.00 | 10.06 | 7.22 | 0.0227 | Yes |
| **Scenario** | 77.40 | 38.70 | 2.00 | 325.22 | 2.73 | 0.0668 | Marginally |
| **Scenario Order** | Omitted from Model | | | | | | No |
| **Probe** | 2696.42 | 674.10 | 4.00 | 325.66 | 47.53 | 0.0000 | Yes |

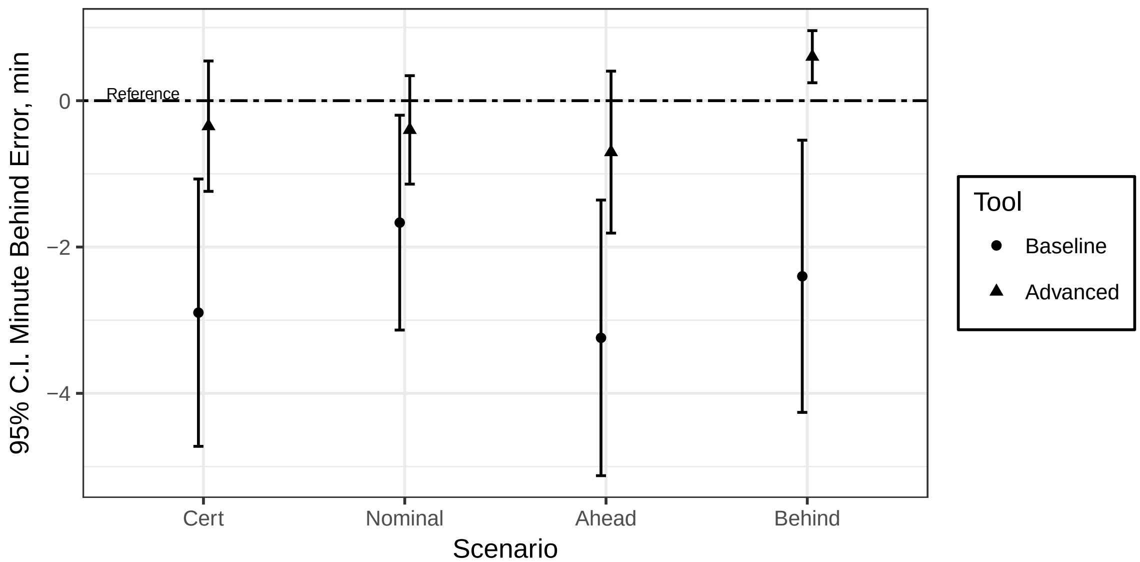



Figure 6.5: Minute Behind error 95% confidence interval results per DSS and scenario.

A Tukey Post-hoc analysis on DSS Tool revealed a statistically significant difference in Minute Behind error ($p \leq 5e^{-9}$) with the Advanced Tool averaging (+)2 minutes more positive error than the Baseline Tool, indicating the Advanced tool tended towards being more conservative. The order in which participants utilized each DSS tool had marginal statistical significance on Minute Behind error ($p \leq 0.057$), where those who utilized the Baseline condition tended to produce lower Minutes Behind estimate errors ($\approx 1$ minute) than those who were trained with the Advanced Tool first, potentially indicating a slight training effect. Finally, as shown in Figure 6.1, all Advanced tool confidence intervals are more tightly bound by $\approx 1$ minute more than the Baseline error results. Additionally, the mean Minute Behind error values using the Advanced Tool tended towards zero error more often than the Baseline. This result indicates the IV operator using the Baseline tool tended to estimate the EV crew were farther ahead of schedule than they actually were (on average between 2 and 5 minutes).

Minute Behind Error - per probe

The Minute Behind calculation was performed at five separate instances during the simulation: once at the end of the first translation activity (tts4), once during the middle of Station 4 activity, again at the end of the second translation activity (tts5), partway through the last station activity (s5) and one final time at the termination of the simulation (s5end). The end of translation activity periods again signified clear transition periods within the timeline and I hypothesized that performing the Minutes Behind calculation at these clear transition periods would be more accurate than in the middle of a Station activity where a reference point, and subsequently the calculation would be more difficult to estimate. Figure 6.6 and 6.7 shows the 95% C.I. Minute Behind Error plots divided by the translation and station probes, respectively.

A LMER using only tts Minute Behind data indicated significant influence in DSS tool and Scenario, only. The Advanced Margin error tended to be approximately (+)1 minute more conservative than Baseline estimates ($p \leq 0.0004$). Significant differences were measured between the Behind and Ahead scenarios. Marginal difference was measured between the Behind and Nominal conditions. In both situations, the Behind condition tended towards a less conservative Minutes Behind error.

Another model was constructed with only station Minute Behind error data where significant influences by DSS, Scenario and Probe were observed. DSS Tool had a statistically significant impact on station minute behind error, users with the Advanced tool on average estimating Minutes Behind (+)3.5 minutes more conservatively than with the Baseline tool. A Tukey Post-hoc analysis revealed statistical significance between both Ahead-Nominal and Behind-Ahead Scenarios. In particular, participants estimated on average nearly 2 minutes less conservatively during the Ahead condition as compared to the Nominal sce-

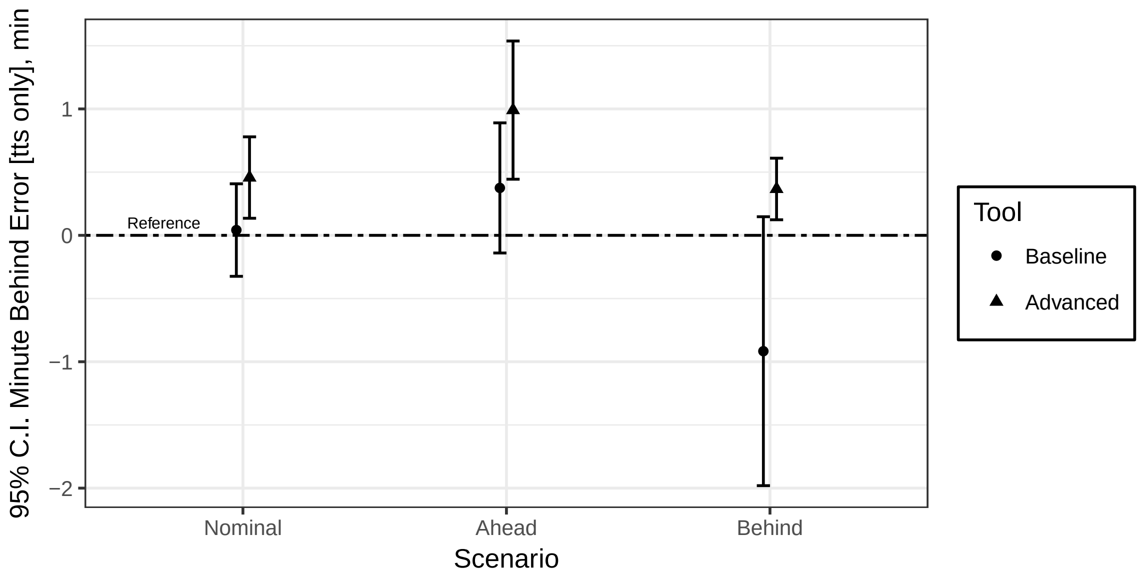



Figure 6.6: Minute Behind error 95% confidence interval results per DSS and scenario for end of translation (tts4 and tts5) calculations only.

nario and 2.4 minutes more conservatively in the Behind scenario compared to the Ahead scenario. Finally, statistically significant differences in minute behind error progressively became less conservative between all probes throughout timeline execution. Between s5 and s4, participants estimated approximately 5 minutes behind than they actually were. The extent of error increases to almost 8 minutes in error between the s5end and s4 probes. Interestingly enough, there was also significant differences between s5 and s5end which were preformed approximately 3 minutes a part. During that time, Minute Behind error drifted in the less conservative direction by almost 3 minutes. These results reveal an important aspect of operations: (1) Conservative estimates are good up to a point, but too much is wasteful. (2) Non-conservative estimates introduce risk and provide a false sense of progress.

Finally, when we look across all scenarios, and look at the temporal changes of the IV's ability to perform the Minutes Behind calculation throughout the 35 minute simulations (e.g. perform first at tts4 ($\approx$ 5 min), then s4 ($\approx$ 11 min), then tts5 ($\approx$ 20 min), then s5 ($\approx$ 32 min), and then finally at s5end (35 min)), there is a gradual deviation or growth in error as shown in Figure 6.8, The drift moves towards a more conservative estimate during Station

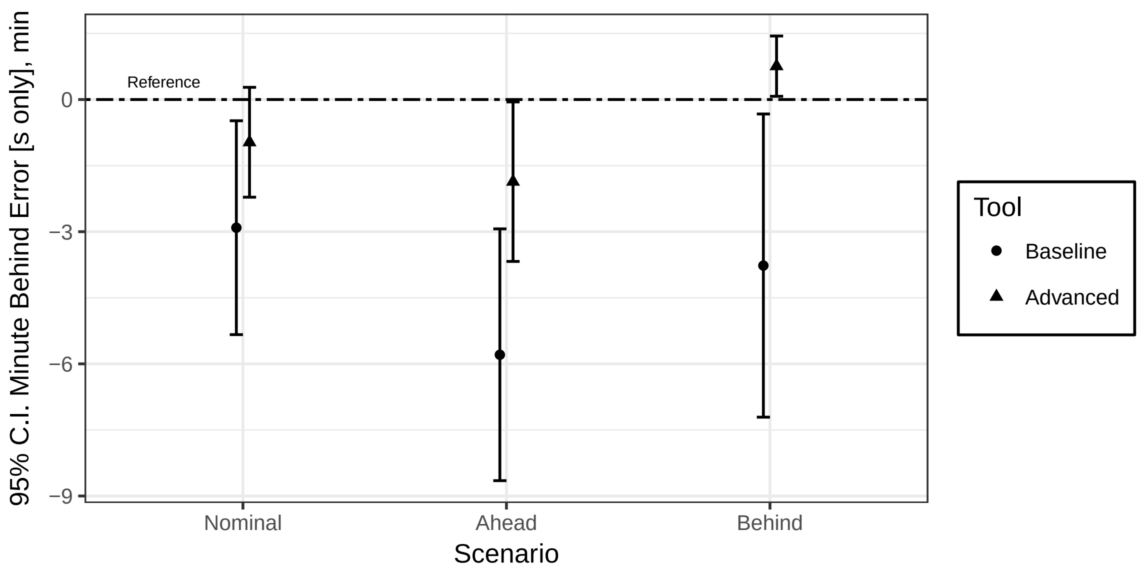



Figure 6.7: Minute Behind error 95% confidence interval results per DSS and scenario for station (s) calculations only.

4 activities, with tts 4 and tts5 providing clear anchor points to establish a more accurate Minute Behind estimate. However, once Station 5 activities progress, the ability for the IV operator to provide an accurate, and conservative estimate becomes more limited. Notably, the Advanced tool helps stem the growth of this error in the less conservative direction and promotes a more conservative estimate at different sections of the timeline. This trend is an artifact of the rules applied to Marvin's internal logic discussed in Chapter 4. Additionally, the confidence intervals surrounding these estimates were tighter with the Advanced tool ($\pm 1.5$ min.) compared to the Baseline tool ($\pm 3$ minutes).

*Confidence Estimates*

For each calculation of the timeline margin, the participant provided a confidence as a way of accounting for any self-perceived error they may have in their timeline margin estimate. The larger the confidence estimate, the less confident the participant was in their margin estimate. The mixed-level modeling results are shown in Table 6.3 and discussed in detail below.

Confidence Estimate - Scenario and DSS Tool

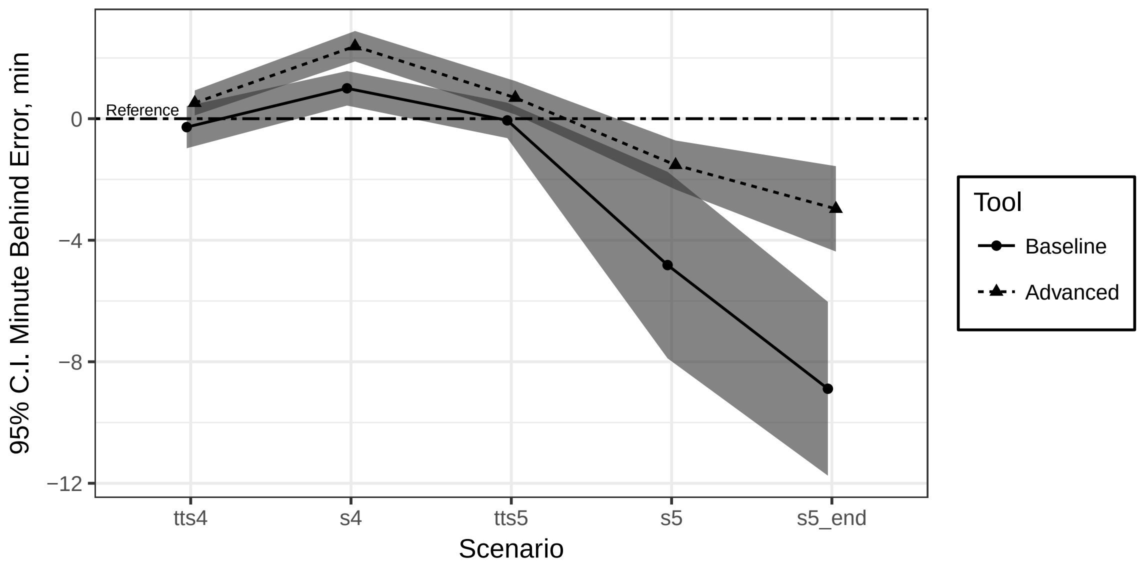



Figure 6.8: Minute behind error 95% confidence per specific probe across all scenarios.

Table 6.4: Confidence estimate ANOVA results summary.

| Independent Variable | Sum Sq | Mean Sq | NumDF | DenDF | F.value | Pr(>F) | Significant Influence |
|---|---|---|---|---|---|---|---|
| Tool | 120.85 | 120.85 | 1.00 | 195.07 | 27.74 | 0.0000 | Yes |
| DSS Order | Omitted from Model | | | | | | No |
| Scenario | 50.62 | 25.31 | 2.00 | 195.22 | 5.81 | 0.0035 | Yes |
| Scenario Order | Omitted from Model | | | | | | No |
| Probe | 66.99 | 33.49 | 2.00 | 195.09 | 7.69 | 0.0006 | Yes |

A Tukey Post-hoc analysis on DSS Tool revealed a statistically significant difference in reported confidence estimates with participants reporting on average 1.5 minutes more confident with the Advanced Tool compared the Baseline Tool. A Tukey post-hoc analysis on Scenario revealed statistical difference between both Behind-Nominal and Behind-Ahead conditions, with participants providing on average larger confidence estimate in the Behind scenario ($\approx 1$ minute more uncertainty). Finally, as shown in Figure 6.9, all Advanced tool confidence intervals are more tightly bound as compared to the Baseline results which indicates the participants generally felt more confident with their answers using the Advanced tool. Outliers as large as -61 and +30 minute Margin errors were observed using the Baseline Tool. However, there is an overall increase in confidence estimates for both

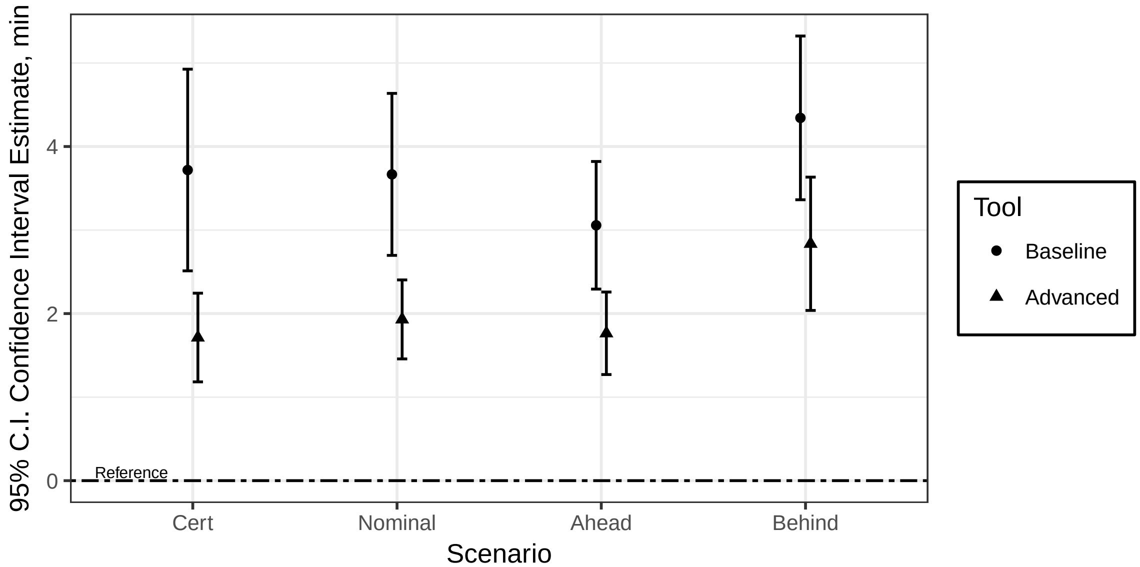



Figure 6.9: Confidence estimate 95% confidence interval results per DSS and scenario.

tools under the Behind scenario condition.

<u>Confidence Estimate - per probe</u>

The confidence estimate was provided at three separate instances that correspond to the margin calculations: once at the end of the first translation activity (tts4), again at the end of the second translation activity (tts5), and then one final time at the termination of the simulation (s5end). The end of translation activity periods again signified clear transition periods within the timeline and I hypothesized that confidence when performing the Margin calculation at these clear transition periods would be higher (hence a lower value) than in the middle of a Station activity where the Margin estimate is more difficult to estimate. Figure 6.10 and 6.11 shows the 95% C.I. Confidence Estimate plots divided by the translation and station probe data, respectively.

The same LMER also revealed statistically different estimates between probes. Specifically, the reported confidence estimates for s5end were on average over 1 minute more than both the tts4 and tts5 probes. Finally, when we look across all scenarios, and look at the temporal changes of the IV's ability to perform the timeline margin calculation throughout the 35 minute simulations (e.g. perform first at tts4, then at tts5, and then finally at s5end)

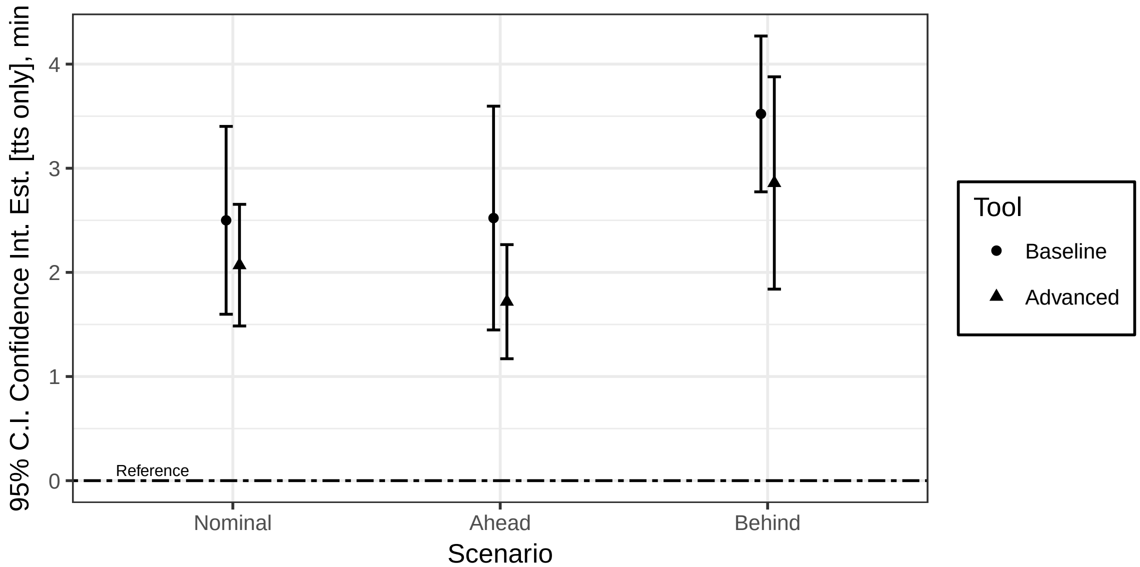



Figure 6.10: Confidence estimate 95% confidence interval results per DSS and scenario for end of translation calculations only.

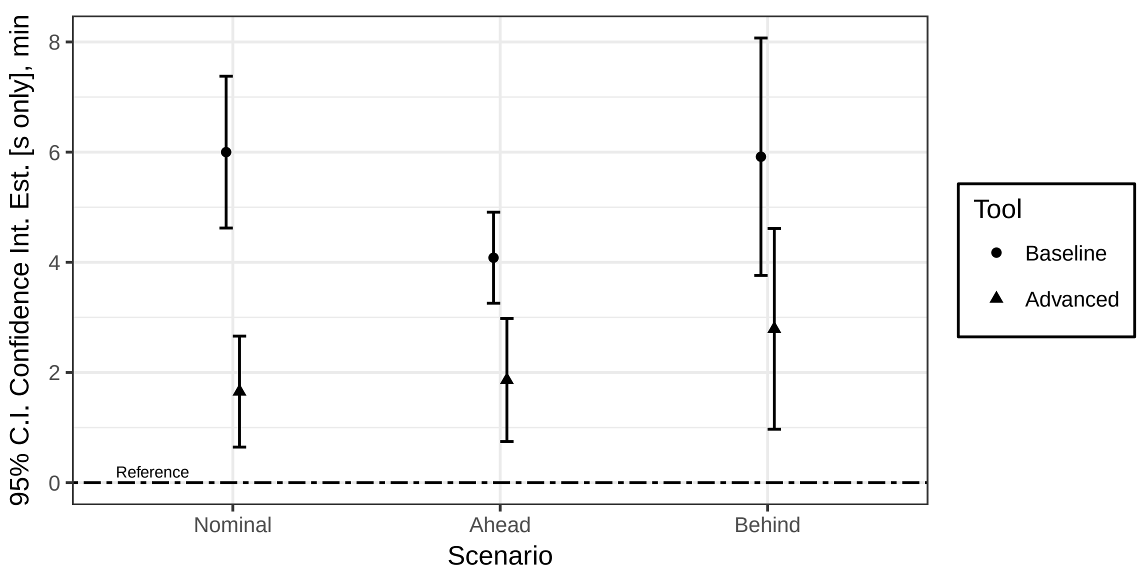



Figure 6.11: Confidence estimate 95% confidence interval results per DSS and scenario for station calculations only.

we see a growth in the confidence estimate as shown in Figure 6.12 at the s5end probe which occurs at the end of the simulation while within Station 5 activities.

Confidence Estimate versus Actual Margin Error

If IV operators could accurately account for the error accrued in their Margin error,

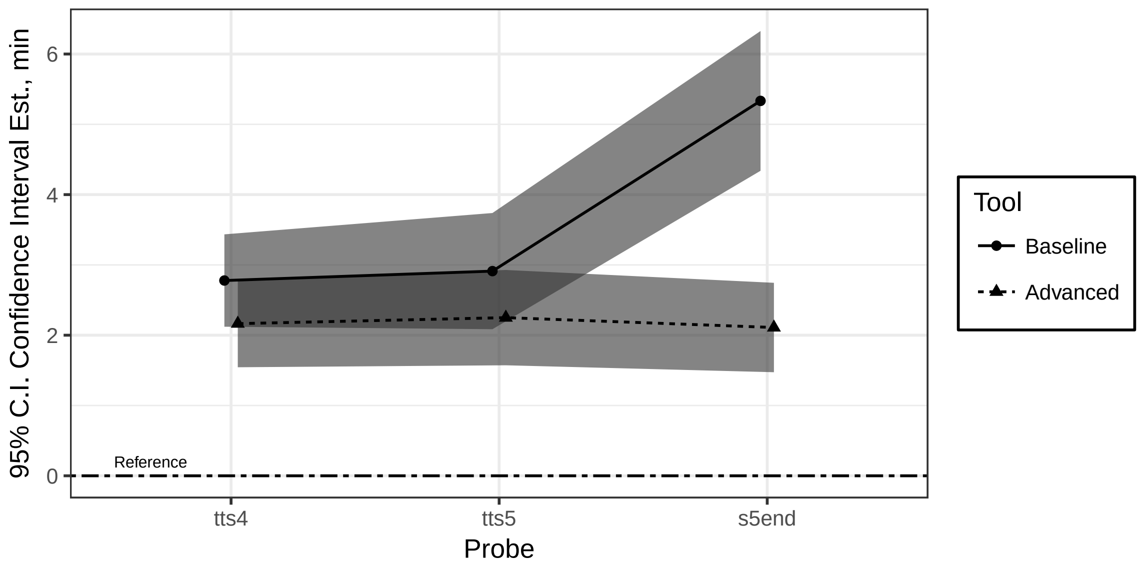



Figure 6.12: Confidence estimate 95% confidence per specific probe across all scenarios.

then that bias could be corrected. To examine if this in fact happened and IV operators could consistently quantify the error in their Margin calculation, each confidence estimate and actual Margin error were compared and categorized based on whether their perceived confidence estimate *Over* estimated the error, *Exactly* accounted for the error, or *Under* estimated the error. Non-parametric analysis techniques were then applied to examine if IV operators exhibited any tendency to account for the error in their Margin estimates.

Figure 6.13 shows a histogram of the categorized data divided by the DSS Tool type. A two-sample Wilcoxon test shows no statistically significant difference between the DSS configurations ($W = 6100, p = 0.28$).

Figure 6.14 shows a histogram of the categorized data divided by the Scenario type. A Pearson's Chi-squared test shows marginal statistical significance between scenarios ($\chi^2 = 9, p = 0.01$). Therefore, there are unequal proportions of IV operators in different testing scenarios scoring in each of the three (Under/Exact/Over) categories.

Figure 6.15 shows a histogram of the categorized data divided by the calculation probe. A Pearson's Chi-squared test shows statistical significance between probes ($\chi^2 = 44, p = 7.3e^{-9}$). Therefore, there are unequal proportions of IV operators in different probes (e.g.

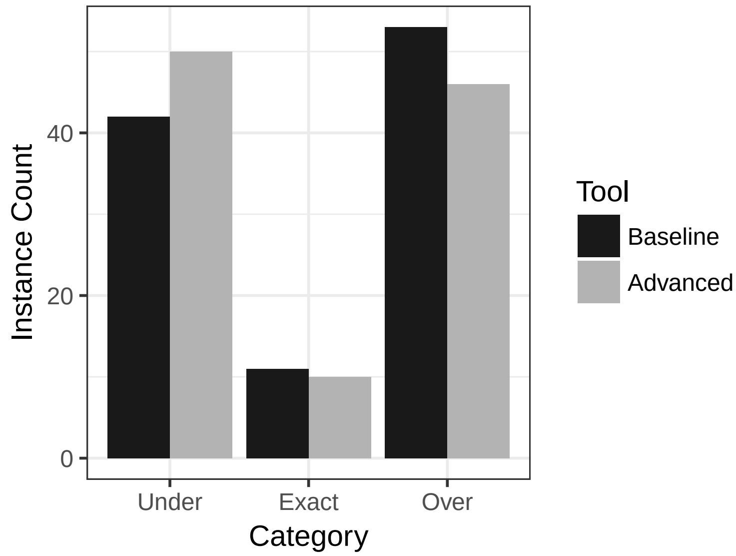



Figure 6.13: Confidence estimate - |actual| margin error per DSS configuration.

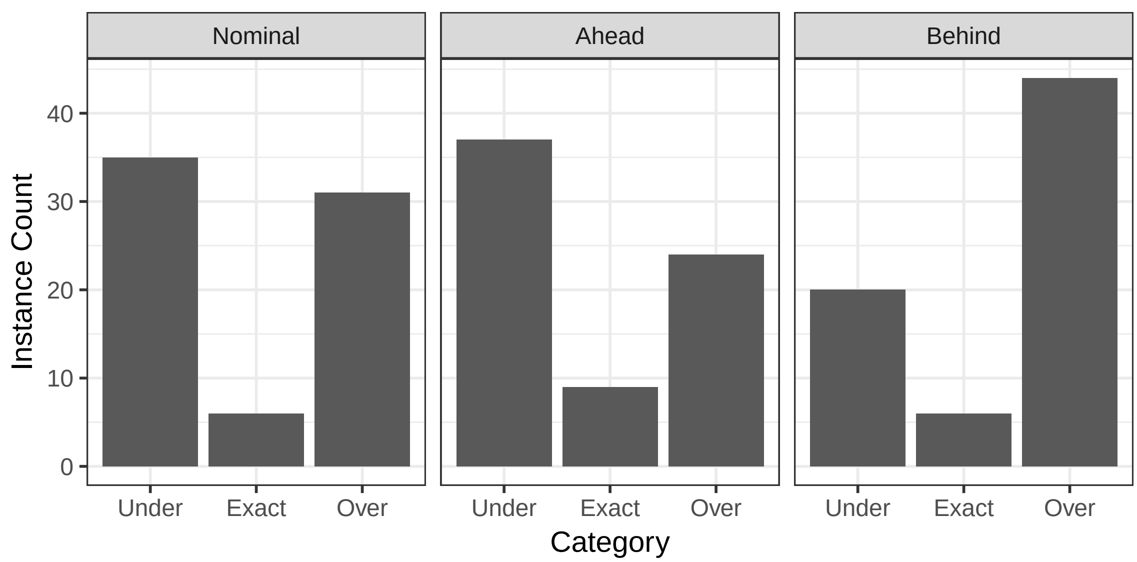



Figure 6.14: Confidence estimate - |actual| margin Error per scenario.

different locations within the timeline) scoring in each of the three (Under/Exact/Over) categories.

*Time to Complete Margin Estimate ($TTC_{Margin}$)*

The time it took for the IV operator to perform the final $TTC_{Margin}$ calculation at the end of each simulation run was record. The larger the duration, the longer it took to obtain a

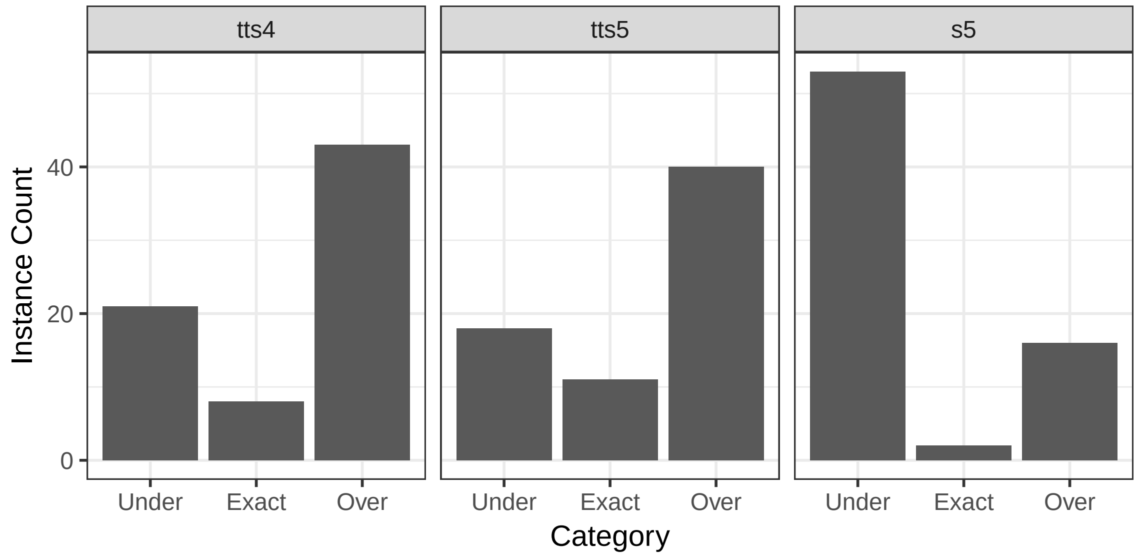



Figure 6.15: Confidence estimate - |actual| margin error per margin calculation probe.

final estimate. The mixed-level modeling results are shown in Table 6.5 and discussed in detail below.

Table 6.5: Time to complete margin estimate ($TTC_{Margin}$) ANOVA results summary.

| Independent Variable | Sum Sq | Mean Sq | NumDF | DenDF | F.value | Pr(>F) | Significant Influence |
|---|---|---|---|---|---|---|---|
| **Tool** | 34.53 | 34.53 | 1.00 | 58.17 | 229.10 | 0.0000 | Yes |
| **DSS Order** | 2.03 | 2.03 | 1.00 | 9.99 | 13.50 | 0.0043 | Yes |
| **Scenario** | Omitted from Model | | | | | | No |
| **Scenario Order** | Omitted from Model | | | | | | No |

Time to complete margin estimate ($TTC_{Margin}$) - DSS tool and order

Only the DSS Tool and DSS Order significantly influences the $TTC_{Margin}$ results. A Tukey Post-hoc analysis on DSS Tool revealed a statistically significant difference in $TTC_{Margin}$ ($p \leq 2e^{-16}$) with the Advanced Tool averaging (+)1.4 minutes quicker in response time than the Baseline Tool, as shown in Figure 6.16. A Tukey Post-hoc analysis on DSS Order revealed a statistical difference indicating that those participants who trained on the Advanced tool first, provided on average a response $\approx 30$ seconds more quickly than those who first trained on the Baseline tool, indicating a potential training effect.

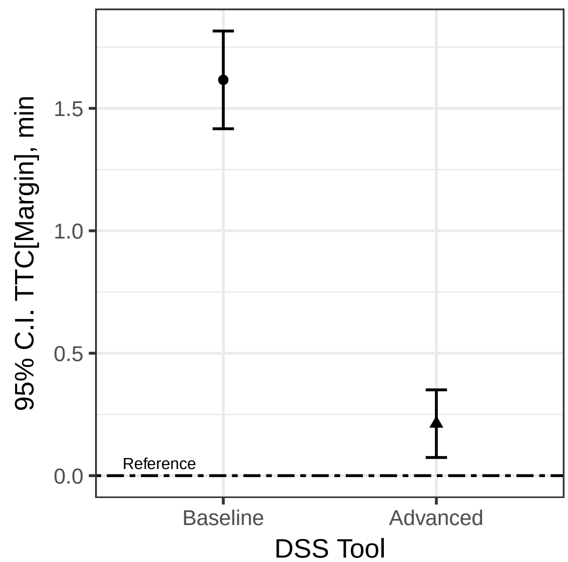



Figure 6.16: Time to complete margin estimate ($TTC_{Margin}$ 95% confidence interval results per DSS across all scenarios.

*Time to Complete Minutes Behind Estimate ($TTC_{MinB}$)*

The time it took for the IV operator to perform the final $TTC_{MinB}$ calculation at the end of each simulation run was record. The larger the duration, the longer it took to obtain a final estimate. The mixed-level modeling results are shown in Table 6.6 and discussed in detail below.

Table 6.6: Time to complete minutes behind estimate ($TTC_{MinB}$) ANOVA results summary.

| Independent Variable | Sum Sq | Mean Sq | NumDF | DenDF | F.value | Pr(>F) | Significant Influence |
|---|---|---|---|---|---|---|---|
| **Tool** | 9.77 | 9.77 | 1.00 | 105.26 | 52.70 | 0.0000 | Yes |
| **DSS Order** | 0.95 | 0.95 | 1.00 | 9.99 | 5.13 | 0.0470 | Yes |
| **Scenario** | Omitted from Model | | | | | | No |
| **Scenario Order** | Omitted from Model | | | | | | No |

Time to Complete Margin Estimate ($TTC_{MinB}$) - DSS Tool and Order

Only the DSS Tool and DSS Order significantly influences the $TTC_{MinB}$ results. A Tukey Post-hoc analysis on DSS Tool revealed a statistically significant difference in $TTC_{MinB}$

($p \leq 3e^{-13}$) with the Advanced Tool averaging $\approx 30$ seconds quicker in response time than the Baseline Tool, as shown in Figure 6.17. A Tukey Post-hoc analysis on DSS Order revealed a statistical difference indicating that those participants who trained on the Advanced tool first ($p \leq 0.024$), provided on average a response $\approx 20$ seconds more quickly than those who first trained on the Baseline tool, indicating a potential training effect.

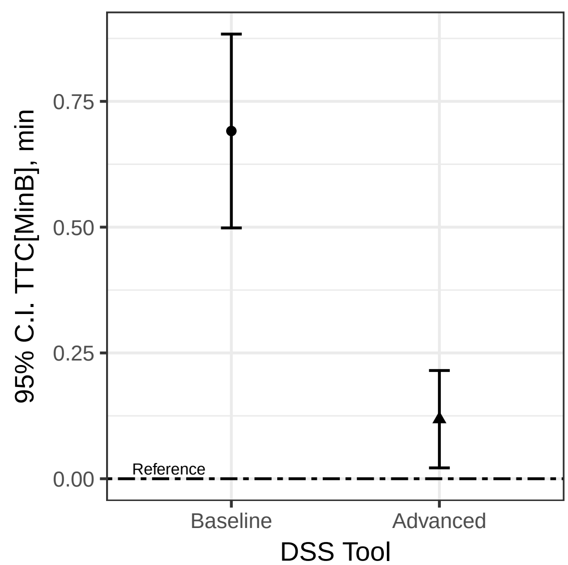



Figure 6.17: Time to complete minute behind estimate ($TTC_{MinB}$ 95% confidence interval results per DSS across all scenarios.

*Step Coverage*

For Station 4 and the first page of Station 5 activities, each EV crew member recorded whether each step of the timeline was discussed or not. The total fraction of steps discussed or covered was quantified for three different step types: Subtasks, High Priority Procedures, and Secondary Priority Procedures. The closer to 1 the fraction of step coverage, the more coverage the IV operator exhibited during execution. The mixed-level modeling results are shown in Table 6.7 and discussed in detail below.

Figure 6.18 shows the 95% C.I. of the fraction of steps covered across each Tool and Scenario condition for each EV crew. A LMER analysis for the Subtask step indicated DSS Tool, Scenario, Scenario Order, and EV crew had a significant influence on Subtask

Table 6.7: Timeline Subtask step coverage ANOVA results summary.

| Independent Variable | Sum Sq | Mean Sq | NumDF | DenDF | F.value | Pr(>F) | Significant Influence |
|---|---|---|---|---|---|---|---|
| **Tool** | 0.11 | 0.11 | 1.00 | 414.02 | 3.24 | 0.0727 | Marginally |
| **DSS Order** | Omitted from Model | | | | | | No |
| **Scenario** | 0.24 | 0.12 | 2.00 | 414.02 | 3.56 | 0.0292 | Yes |
| **Scenario Order** | 0.68 | 0.14 | 5.00 | 6.00 | 4.11 | 0.0572 | Marginally |
| **EV Crew** | 0.48 | 0.48 | 1.00 | 414.00 | 14.39 | 0.0002 | Yes |

step coverage. A Tukey post-hoc analysis indicated a marginally significant difference between DSS tools ($p \leq 0.072$). Participants on average coverage 3% more Subtasks when using the Advanced tool, as compared to the Baseline tool. A Tukey post-hoc analysis indicated a significant difference between Scenario conditions (Behind-Ahead) ($p \leq 0.024$) where nearly 6% more Subtasks were coverage under Behind conditions as compared to the Ahead scenario. Between EV crew, EV2 Subtasks were on average covered nearly 7% less than the EV1 subtasks which indicates an overall preference of coverage between the EV crew timeline types.

Table 6.8: Timeline High Priority Procedure step coverage ANOVA results summary.

| Independent Variable | Sum Sq | Mean Sq | NumDF | DenDF | F.value | Pr(>F) | Significant Influence |
|---|---|---|---|---|---|---|---|
| **Tool** | 1.13 | 1.13 | 1.00 | 320.04 | 15.05 | 0.0001 | Yes |
| **DSS Order** | Omitted from Model | | | | | | No |
| **Scenario** | Omitted from Model | | | | | | No |
| **Scenario Order** | Omitted from Model | | | | | | No |
| **EV Crew** | 1.45 | 1.45 | 1.00 | 320.00 | 19.25 | 0.0000 | Yes |

A LMER analysis, as shown in Table 6.8, for the High Priority Procedure step indicated DSS Tool and EV crew had a significant influence on High Priority Procedure step coverage. A Tukey post-hoc analysis indicated a significant difference between DSS tools ($p \leq 0.0001$). Participants on average covered 11% more High Priority Procedures when using the Advanced tool, as compared to the Baseline tool. Between EV crew, EV2 High

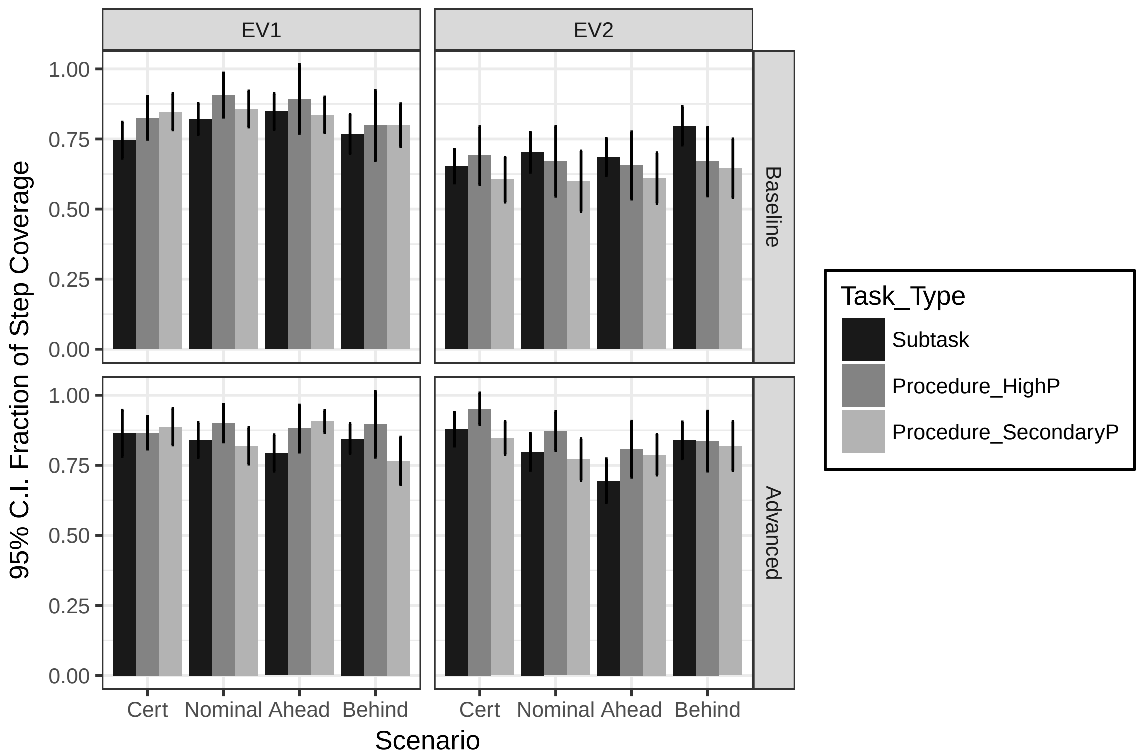


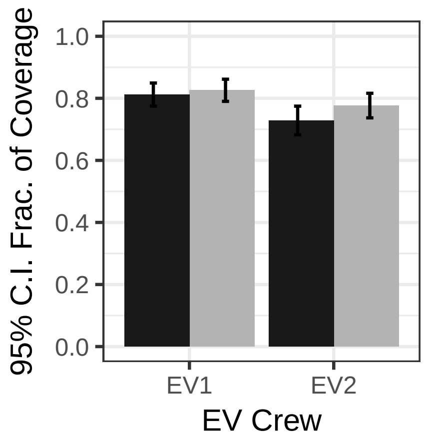

Figure 6.18: Step coverage 95% confidence interval results per DSS, EV crew, across all scenarios and step types.

Priority Procedure steps were on average covered nearly 14% less than the EV1 steps.

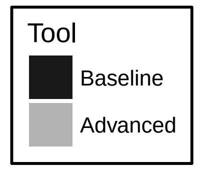
Table 6.9: Timeline Secondary Priority Procedure step coverage ANOVA results summary.

| Independent Variable | Sum Sq | Mean Sq | NumDF | DenDF | F.value | Pr(>F) | Significant Influence |
|---|---|---|---|---|---|---|---|
| **Tool** | 0.81 | 0.81 | 1.00 | 416.03 | 14.52 | 0.0002 | Yes |
| **DSS Order** | 0.31 | 0.31 | 1.00 | 10.00 | 5.57 | 0.0399 | Yes |
| **Scenario** | Omitted from Model | | | | | | No |
| **Scenario Order** | Omitted from Model | | | | | | No |
| **EV Crew** | 1.71 | 1.71 | 1.00 | 416.00 | 30.53 | 0.0000 | Yes |

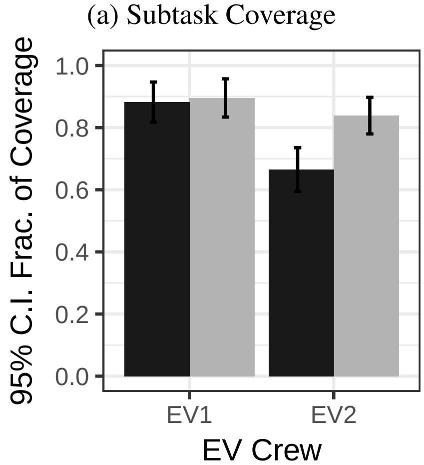
A final LMER analysis, as shown in Table 6.9, was performed for the Secondary Priority Procedure step which also indicated DSS Tool, DSS Order and EV crew had a significant influence on Secondary Priority Procedure step coverage. A Tukey post-hoc analysis indicated a significant difference between DSS tools ($p \leq 0.0001$). Participants on average covered 9% more Secondary Priority Procedures when using the Advanced tool, as com-



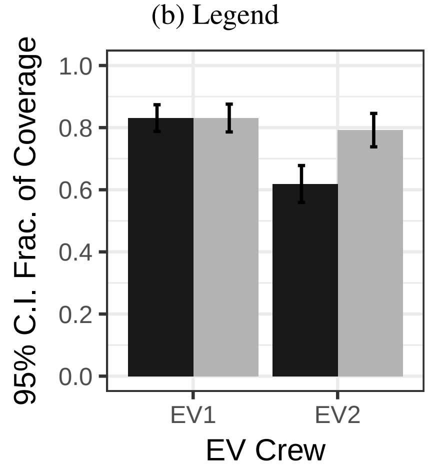

(a) Subtask Coverage




(b) Legend




(c) High priority procedure coverage




(d) Secondary priority procedure coverage

Figure 6.19: 95% confidence interval of step coverage per DSS and EV crew.

pared to the Baseline tool. Between EV crew, EV2 Secondary Priority Procedure steps were on average covered nearly 13% less than the EV1 steps. Finally, a significant effect was found in the DSS run order, where those subjects who utilized the Advanced tool first covered nearly 14% more secondary procedure steps compared to those who utilized the Baseline first. Figure 6.19 shows a summary of the results of the step coverage based on the primary factors of influence for each step type.

*IV Communication Behavior*

For all steps included in Station 4 and the first page[1] of Station 5 activities, each EV crew member recorded the type of communication spoken by the IV operator using four categories that describe the timing of communication that occurred relative to the EV scripted timeline. The categories included: Proactive, On Time, Retroactive, or Missed. A LMER was created for each category of communication type and analyzed for factor significance. The model results are summarized in subsequent sections below.

Figure 6.20 shows a stacked bar chart of the fraction of step coverage decomposed by type of communication. the 95% C.I. of the fraction of steps covered by participants across each Tool and Scenario condition for each EV crew.

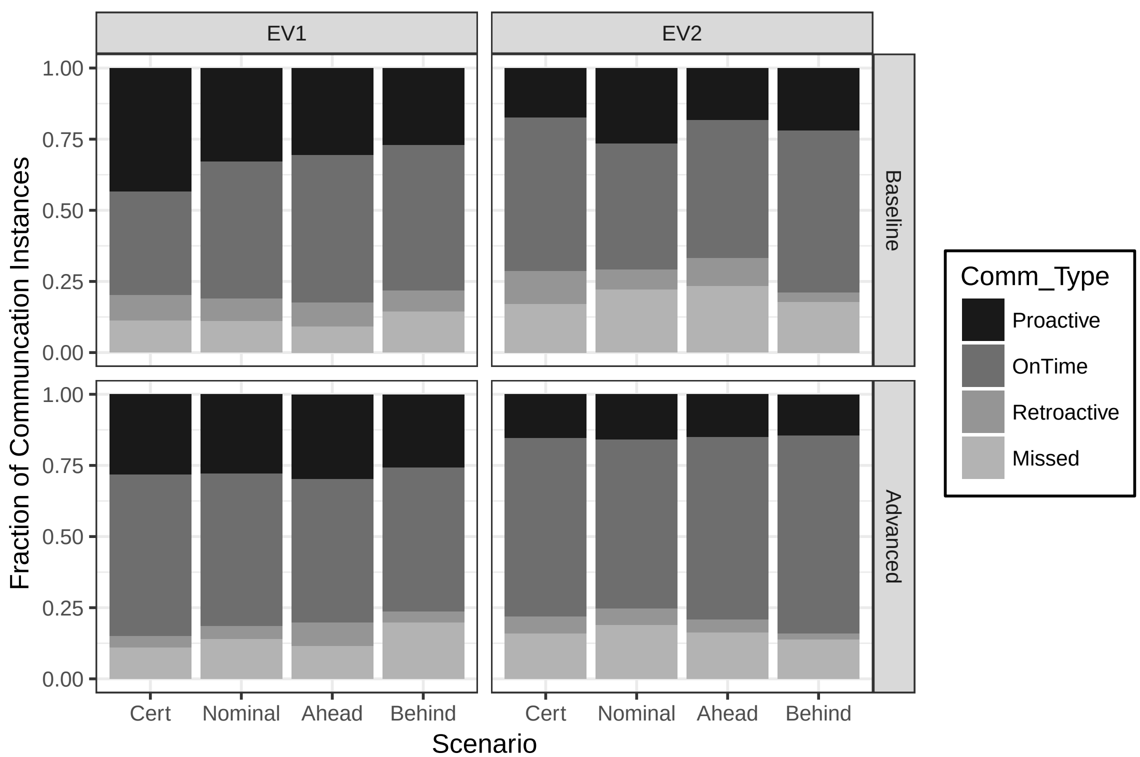



Figure 6.20: IV communication behavior results per DSS, EV crew, across all scenarios and communication type.

[1]Each scenario reached different ending positions within Station 5 However all scenarios covered at least the first page of Station 5. Therefore, to examine the communication behavior over equivalent timeline periods, all of Station 4 and the first page of Station 5 was used.

Table 6.10: IV Proactive communication behavior ANOVA results summary.

| Independent Variable | Sum Sq | Mean Sq | NumDF | DenDF | F.value | Pr(>F) | Significant Influence |
|---|---|---|---|---|---|---|---|
| **Tool** | 0.24 | 0.24 | 1.00 | 416.03 | 4.24 | 0.0402 | Yes |
| **DSS Order** | Omitted from Model | | | | | | No |
| **Scenario** | Omitted from Model | | | | | | No |
| **Scenario Order** | Omitted from Model | | | | | | No |
| **EV Crew** | 1.12 | 1.12 | 1.00 | 416.00 | 19.87 | 0.0000 | Yes |

The LMER of Proactive communication, as shown in Table 6.10, revealed a significant influence in DSS Tool and EV Crew. Participants tended to communicate more proactively using the Baseline tool ($\approx$ 5% more) than when using the Advanced tool. Between EV crew, participants communicated 10% more often on average proactively towards the EV1 as compared to the EV2.

Table 6.11: IV On Time communication behavior ANOVA results summary.

| Independent Variable | Sum Sq | Mean Sq | NumDF | DenDF | F.value | Pr(>F) | Significant Influence |
|---|---|---|---|---|---|---|---|
| **Tool** | 0.66 | 0.66 | 1.00 | 414.04 | 10.01 | 0.0017 | Yes |
| **DSS Order** | Omitted from Model | | | | | | No |
| **Scenario** | 0.24 | 0.12 | 2.00 | 414.04 | 1.80 | 0.1661 | No |
| **Scenario Order** | Omitted from Model | | | | | | No |
| **EV Crew** | 0.39 | 0.39 | 1.00 | 414.00 | 5.98 | 0.0149 | Yes |

The LMER of On Time communication, as shown in Table 6.11, revealed a significant influence in DSS Tool , and EV Crew. Participants tended to communicate more On Time using the Advanced tool ($\approx$ 8% more) than when using the Baseline tool. Between EV crew, participants communicated 6% more often on average on time towards the EV2 as compared to the EV1.

The LMER of Retroactive communication, as shown in Table 6.12, revealed a significant influence in DSS Tool ($p \leq 0.036$). Participants tended to communicate more retroactively using the Baseline tool ($\approx 3\%$ more) than when using the Advanced tool.

Table 6.12: IV Retroactive communication behavior ANOVA results summary.

| Independent Variable | Sum Sq | Mean Sq | NumDF | DenDF | F.value | Pr(>F) | Significant Influence |
|---|---|---|---|---|---|---|---|
| Tool | 0.07 | 0.07 | 1.00 | 417.11 | 4.44 | 0.0357 | Yes |
| DSS Order | Omitted from Model | | | | | | No |
| Scenario | Omitted from Model | | | | | | No |
| Scenario Order | Omitted from Model | | | | | | No |

Table 6.13: IV Missed communication behavior ANOVA results summary.

| Independent Variable | Sum Sq | Mean Sq | NumDF | DenDF | F.value | Pr(>F) | Significant Influence |
|---|---|---|---|---|---|---|---|
| **Tool** | Omitted from Model | | | | | | No |
| **DSS Order** | Omitted from Model | | | | | | No |
| **EV Crew** | 0.32 | 0.32 | 1.00 | 417.00 | 9.42 | 0.0023 | Yes |
| **Scenario** | Omitted from Model | | | | | | No |
| **Scenario Order** | 2.34 | 0.47 | 5.00 | 6.00 | 13.69 | 0.0031 | Yes |

Finally, the LMER of Missed communication, as shown in Table 6.13, revealed a significant influence in EV Crew ($p \leq 0.002$) and Scenario Order for multiple order combinations. Participants tended to miss more EV2 steps ($\approx 5\%$ more) than EV1 steps. Interestingly, the Missed communication category was significantly influenced by a multitude of Scenario Order combinations. For the sake of brevity, I do not list each combination in detail.

*Numeric/Alert Event Recognition*

The act of acknowledging numeric telemetry throughout the simulation was recorded. The results are presented as a fraction of events successfully acknolwedged. The mixed-level model results are summarized Table 6.16 and discussed below.

A LMER analysis indicated statistical influence of DSS Tool and Order on the fraction of telemetry events acknowledged. A Tukey post-hoc analysis showed that participants who utilized the Advanced tool on average acknowledged 17% more alerts than when using

Table 6.14: Numeric event recognition ANOVA results summary.

| Independent Variable | Sum Sq | Mean Sq | NumDF | DenDF | F.value | Pr(>F) | Significant Influence |
|---|---|---|---|---|---|---|---|
| **Tool** | 0.53 | 0.53 | 1.00 | 59.00 | 9.45 | 0.0032 | Yes |
| **DSS Order** | 0.20 | 0.20 | 1.00 | 10.00 | 3.51 | 0.0906 | Marginally |
| **Scenario** | Omitted from Model | | | | | | No |
| **Scenario Order** | Omitted from Model | | | | | | No |

the Baseline tool. Additionally, those participants who trained on the Advanced tool first on average acknowledged 17% more alerts over those who utilized the Baseline tool first. Figure 6.21 fraction of telemetry events acknowledged by participants across each Tool and Scenario condition.

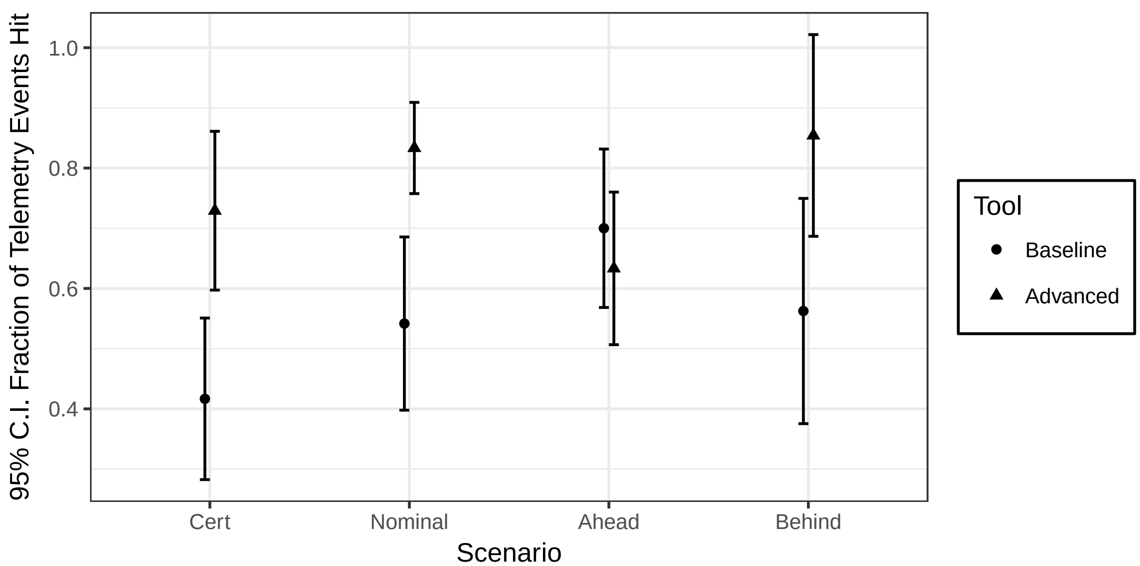



Figure 6.21: Numeric telemetry event fraction hit 95% confidence interval results per DSS across all scenarios.

*Trend Event Recognition*

Similar to numeric event recognition, the trend event recognition involved acknowledging deviations in the graphical displays from established trends in the graphs. The model results are summarized Table 6.15 and the subsequent sections below.

Table 6.15: Trend event recognition ANOVA results summary.

| Independent Variable | Sum Sq | Mean Sq | NumDF | DenDF | F.value | Pr(>F) | Significant Influence |
|---|---|---|---|---|---|---|---|
| **Tool** | 0.02 | 0.02 | 1.00 | 57.00 | 1.00 | 0.3221 | No |
| **DSS Order** | Omitted from Model | | | | | | No |
| **Scenario** | 0.04 | 0.02 | 2.00 | 57.00 | 1.02 | 0.3676 | No |
| **Scenario Order** | Omitted from Model | | | | | | No |

No statistical differences were found in the LMER analysis. Figure 6.22 shows the 95% C.I. of the fraction of numeric telemetry events acknowledged by participants across each Tool and Scenario condition.

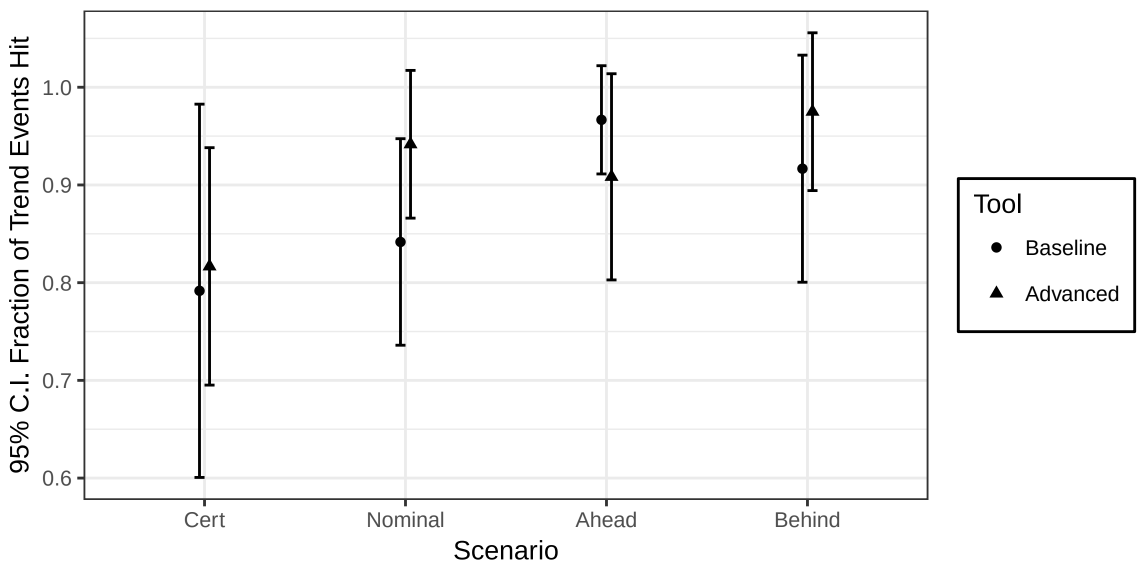



Figure 6.22: Trend event fraction of events hit 95% confidence interval results per DSS across all scenarios.

In addition to examining for the simulated trend events, participants had the opportunity to provide extra trend events as they saw fit throughout the simulations. The surplus events included providing repeative or updates summaries on initial scripted events or noticing more sutble events that were not specifically being tested. Figure 6.23 shows the 95% C.I. of the fraction of surplus trend events acknowledged by participants across each Tool and Scenario condition. A LMER of the fraction of surplus events provided indicated a significant influence with DSS Tool ($p \leq 0.004$). So while there were no statistical differences in the trend events reported between the DSS tools for the scripted events, the Advanced tool tended to promote over 30% more reporting of additional trend events.

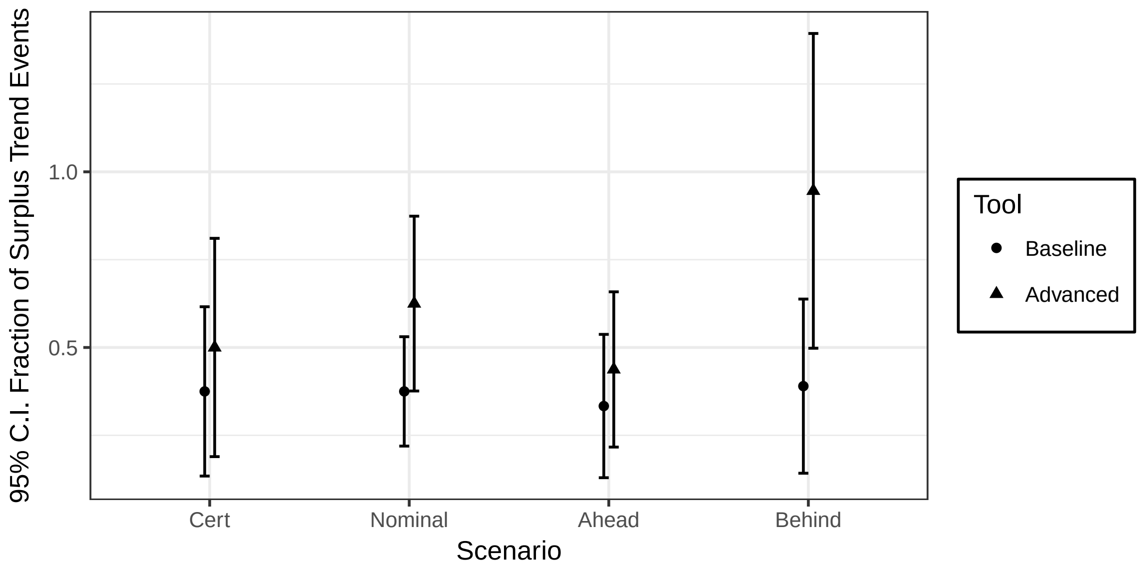



Figure 6.23: Trend event fraction of surplus events 95% confidence interval results per DSS across all scenarios.

*Trend Event Response Time*

For each recognized Trend event, the time to respond to the event was recorded. The model results are summarized Table 6.16.

Table 6.16: Trend event response time ANOVA results summary.

| Independent Variable | Sum Sq | Mean Sq | NumDF | DenDF | F.value | Pr(>F) | Significant Influence |
|---|---|---|---|---|---|---|---|
| **Tool** | Omitted from Model | | | | | | No |
| **DSS Order** | Omitted from Model | | | | | | No |
| **Scenario** | Omitted from Model | | | | | | No |
| **Scenario Order** | 70.02 | 14.00 | 5.00 | 5.91 | 2.24 | 0.1790 | No |

No statistical differences were found in the LMER analysis. Figure 6.24 shows the 95% C.I. of the response times for the trend events acknowledged by participants across each

Tool and Scenario condition.

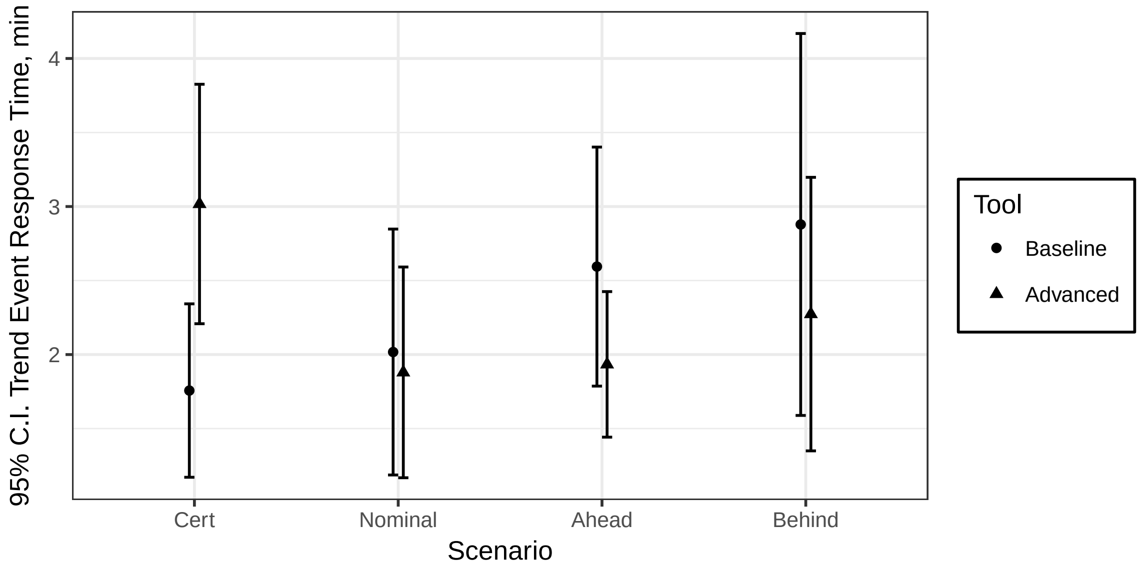



Figure 6.24: Trend event response time 95% confidence interval results per DSS across all scenarios.

*IV-MCC Dialog Exchange*

To quantify the dialog exchange between the IV and MCC, three variables were measured: (1) the Round-trip (RT) message response time defined as the time between the initial question asked by EV to when the IV tells the EV the corresponding answer provided by MCC, (2) the fraction of MCC messages acknowledged by the IV operator and (3) the corresponding response time of acknowledgement. The mixed-level model results are summarized in the subsequent sections below.

Table 6.17: IV-MCC dialog - Messages Acknowledged ANOVA results summary.

| Independent Variable | Sum Sq | Mean Sq | NumDF | DenDF | F.value | Pr(>F) | Significant Influence |
|---|---|---|---|---|---|---|---|
| **Tool** | 0.10 | 0.10 | 1.00 | 57.00 | 2.52 | 0.1181 | No |
| **DSS Order** | Omitted from Model | | | | | | No |
| **Scenario** | 0.10 | 0.05 | 2.00 | 57.00 | 1.27 | 0.2900 | No |
| **Scenario Order** | Omitted from Model | | | | | | No |

A LMER analysis of the fraction of MCC messaged acknowledged, as shown in Table 6.17, revealed no statistical differences among any of the independent variables. Figure 6.25 shows the 95% C.I. of the fraction of MCC messages acknowledged by the IV across each Tool and Scenario condition.

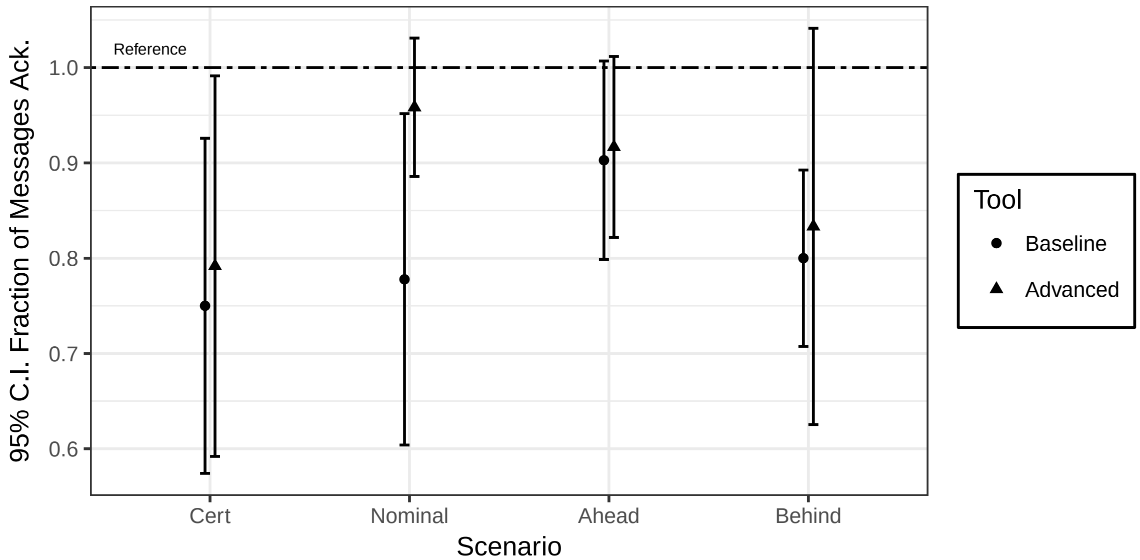



Figure 6.25: Fraction of MCC messages acknowledged 95% confidence interval results per DSS across all scenarios.

Table 6.18: IV-MCC dialog - Response Time ANOVA results summary.

| Independent Variable | Sum Sq | Mean Sq | NumDF | DenDF | F.value | Pr(>F) | Significant Influence |
|---|---|---|---|---|---|---|---|
| **Tool** | 21.24 | 21.24 | 1.00 | 344.30 | 3.86 | 0.0501 | Marginally |
| **DSS Order** | Omitted from Model | | | | | | No |
| **Scenario** | Omitted from Model | | | | | | No |
| **Scenario Order** | Omitted from Model | | | | | | No |

A reduced LMER analysis for the response times of the acknowledged MCC messages, as shown in Table 6.18, revealed a marginally significant difference between DSS tools ($p \leq 0.05$). IV operators utilizing the Advanced tool were more likely to acknowledge MCC messages on average 30 seconds faster than those using the Baseline Tool. Figure 6.26 shows the 95% C.I. of the response times of messages acknowledged by the IV across each Tool and Scenario condition.

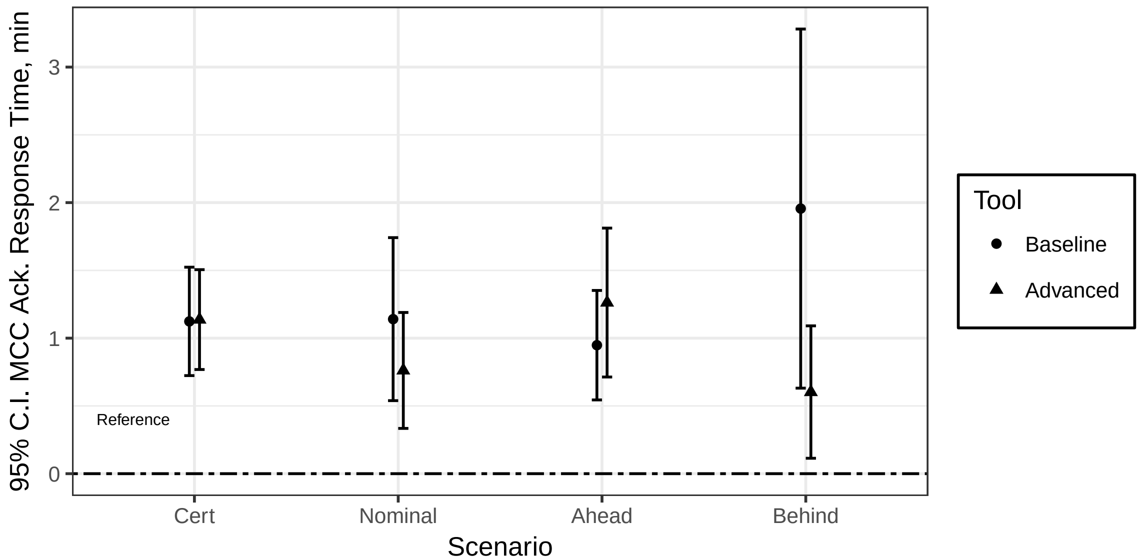



Figure 6.26: Response Time for message acknowledgment 95% confidence interval results per DSS across all scenarios.

Table 6.19: IV-MCC dialog - Round-Trip Response Time ANOVA results summary.

| Independent Variable | Sum Sq | Mean Sq | NumDF | DenDF | F.value | Pr(>F) | Significant Influence |
|---|---|---|---|---|---|---|---|
| **Tool** | 40.97 | 40.97 | 1.00 | 51.16 | 4.00 | 0.0509 | Marginally |
| **DSS Order** | Omitted from Model | | | | | | No |
| **Scenario** | 47.85 | 23.93 | 2.00 | 49.44 | 2.34 | 0.1074 | No |
| **Scenario Order** | Omitted from Model | | | | | | No |

Finally, a LMER analysis of the round trip communication duration of information exchange, as shown in Table 6.19, revealed a marginally difference between DSS tools ($p \leq 0.05$). IV operators utilizing the Advanced tool were on average able relay MCC input to the EV crew on average ≈1.6 minutes more quickly than those using the Baseline Tool. This measurement incorporates both the time it takes to send the initial question to MCC via the text client and then receive and relay the response to the EV crew member. Figure 6.27 shows the 95% C.I. of the response times of the round-trip (R.T.) message facilitated by the IV across each Tool and Scenario condition.

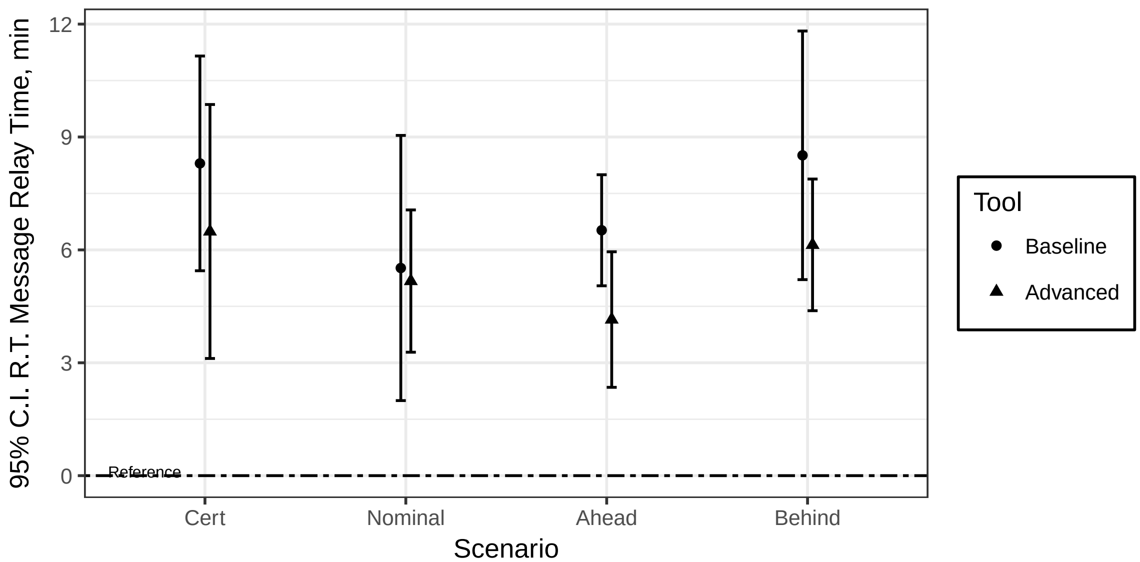



Figure 6.27: Round-trip (RT) message response time 95% confidence interval results per DSS across all scenarios.

### 6.1.2 Survey Assessments

A suite of survey assessments were applied as a means to explore subjective user feedback information. The remainder of this section describes these results in the following order: Operator Proficiency Ratings, NASA Task Load Index (TLX) scores, Cognitive Support Assessment scores, and Interaction Assessment scores.

*Operator Proficiency Rating*

For each Certification and Nominal Scenario condition, EV1, EV2 and the study practitioner (myself) assessed the IV operators performance along a number of dimensions to assess operator proficiency (See Appendix A.5 for details). The mixed-model results are summarized Table 6.20 and described below.

A LMER analysis revealed statistically significant differences across DSS Tool, Scenario and Rater. Participants who utilized the Advanced tool were perceived to be on average 20% more proficient than when using the Baseline Tool. Participants were also rated on average 12% more proficient under the Nominal scenario as compared to the Certifica-

Table 6.20: IV operator proficiency ANOVA results summary.

| Independent Variable | Sum Sq | Mean Sq | NumDF | DenDF | F.value | Pr(>F) | Significant Influence |
|---|---|---|---|---|---|---|---|
| Tool | 40.04 | 40.04 | 1.00 | 3440.00 | 126.53 | 0.0000 | Yes |
| Scenario | 13.25 | 13.25 | 1.00 | 3440.00 | 41.87 | 0.0000 | Yes |
| Rater | 8.36 | 4.18 | 2.00 | 3440.00 | 13.20 | 0.0000 | Yes |

tion simulation. Finally, from a rating perspective, the Practitioner consistently rated the IV operator on average 10% more conservatively as compared to the EV crew who rated comparatively to each other.

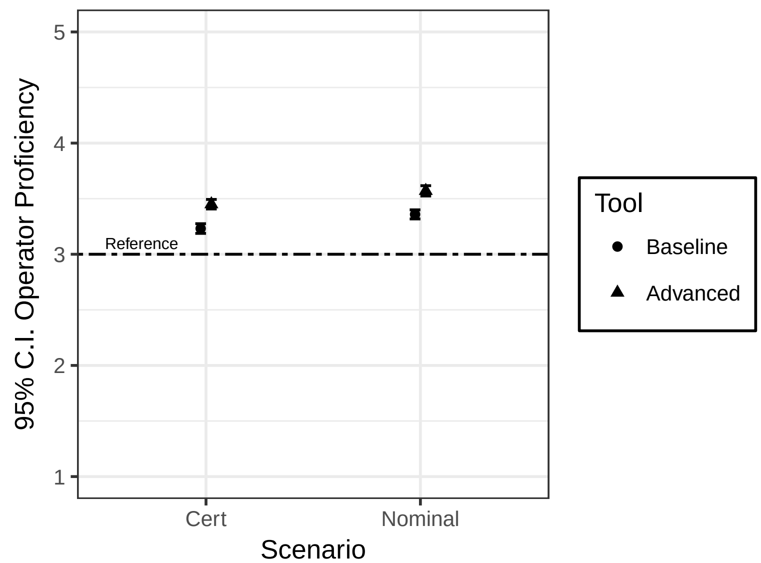



Figure 6.28: Aggregate IV operator proficiency scores for the cert and nominal scenario conditions for each DSS tool.

Figure 6.29 shows the differences of means between Nominal and Cert scenarios for each participant and DSS tool. The intent here is to observe positive or neutral values which indicates the IV operator performed at least as adequately as they performed in their certification simulation.

Figures 6.30 shows the differences of means between Advanced DSS and Baseline DSS under Nominal scenarios for each participant. Positive values indicate the IV operator was observed to be more proficient using the Advanced DSS. This was indeed observed across all participants except for two who showed slight decline in overall proficiency.

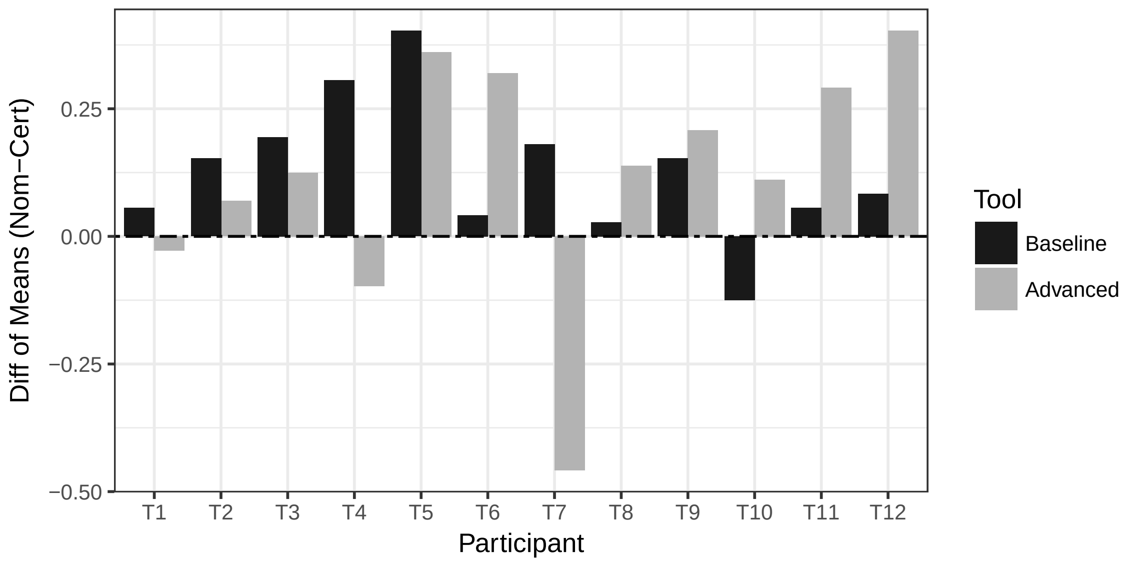



Figure 6.29: Different of mean proficiency scores for each participant using each DSS tool.

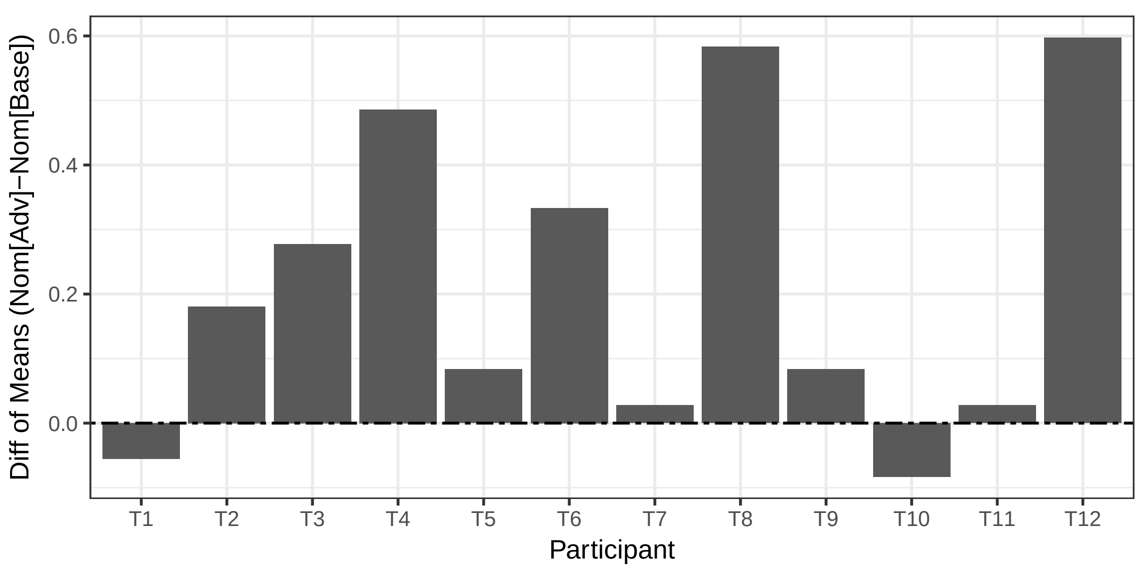



Figure 6.30: Different of mean proficiency scores between the Nominal test conditions (Advanced minus Baseline) for each participant.

*NASA Task Load Index (TLX)*

NASA TLX scores (both composite and individual subscales) were analyzed for the influences of the independent variables. The Physical subscale was omitted from all TLX analyses given its lack of applicability to the simulation environment. The mixed-model results are summarized Table 6.21 and described below.

Table 6.21: Composite TLX score ANOVA results summary.

| Independent Variable | Sum Sq | Mean Sq | NumDF | DenDF | F.value | Pr(>F) | Significant Influence |
|---|---|---|---|---|---|---|---|
| **Tool** | 953.39 | 953.39 | 1.00 | 59.00 | 87.76 | 0.0000 | Yes |
| **DSS Order** | Omitted from Model | | | | | | No |
| **Scenario** | Omitted from Model | | | | | | No |
| **Scenario Order** | Omitted from Model | | | | | | No |

Composite TLX Scores - Scenario and DSS Tool

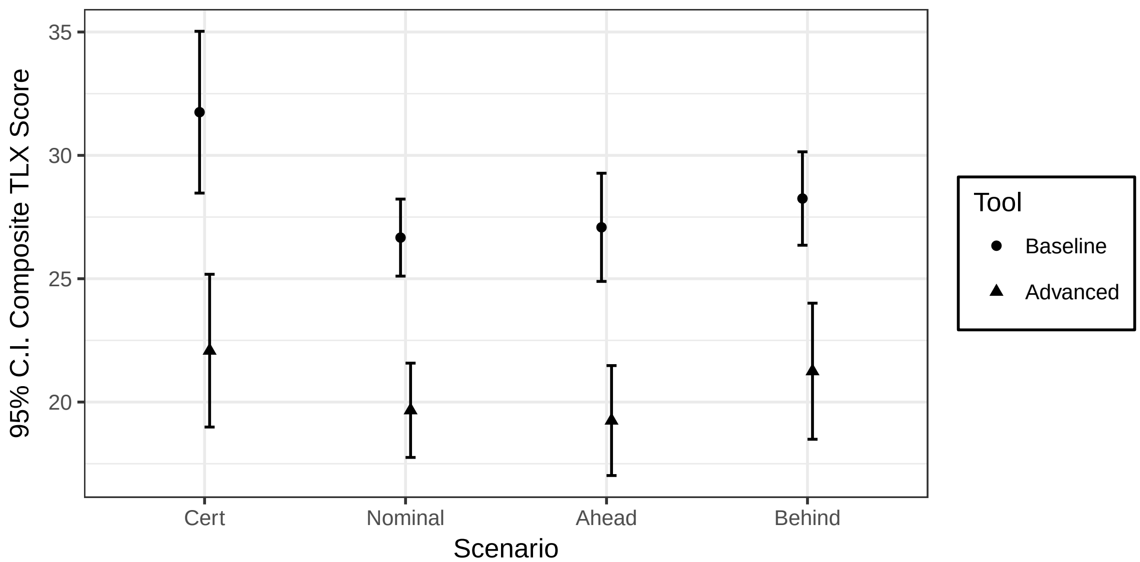



Figure 6.31: Composite TLX scores with 95% confidence interval results per DSS and scenario.

A Tukey Post-hoc analysis on DSS Tool revealed a statistically significant difference in reported composite TLX demand with participants reporting on average 7-points lower (less demanding) when using the Advanced Tool compared the Baseline Tool. Figure 6.31 shows the composite TLX scores across DSS Tool and Scenario for completeness.

Subscale TLX Scores - Scenario and DSS Tool

Figure 6.32 shows the respective subscale scores for each TLX subscale. A LMER was applied to each subscale data set to test for the impact of Tool and Scenario and are

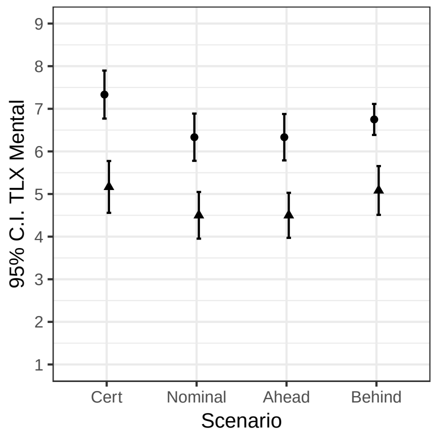
Table 6.22: TLX subscale significance level summary.

| | | TLX Sub-scales | | | | |
|---|---|---|---|---|---|---|
| | | Mental | Temporal | Performance | Effort | Frustration |
| Tool | $p \leq$ | 0.000 | 0.000 | 0.071 | 0.000 | 0.000 |
| Scenario | $p \leq$ | 0.058 | 0.214 | 0.952 | 0.272 | 0.302 |

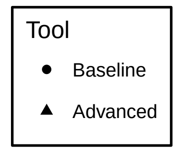
summarized in Table 6.22. All subscales were found to be significantly influenced by DSS Tool, except for Performance, which was found to be marginally significant. Scenario condition did not have any significant statistical influence on the subscales; however, there was a marginally significant influence regarding Mental demand. A Tukey post-hoc test however did not reveal any statistical difference between scenario conditions.

*Cognitive Support Assessment*

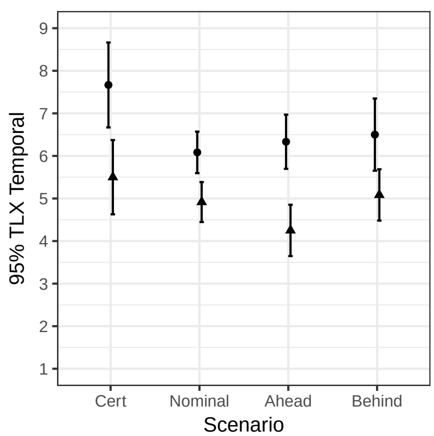
After completing each experimental run with each DSS tool, the participants were asked to comment on the effectiveness of the DSS tools. Participants were asked to rate the overall effectiveness on a 5 point likert scale that ranged from 'Not Effective at All' to 'Extremely Effective' for 15 questions that spanned a variety of topics experienced by the IV operator. Table 6.23 shows the heat maps of frequency of responses across all scenarios for each DSS tool. The bulk of responses for the Advance DSS tended towards being more favorable than the Baseline Tool. Notably, no questions were rated as 'Not Effective at All' and only seven questions were rated 'Slightly Effective.' Out of those rated 'Slightly Effective', none received more than 9% of the overall responses. Additionally, a Kruskal-Wallis non-parametric test was applied to determine statistically significant differences between response distributions of the DSS tools for the ordinal dependent variable, level of effectiveness. Significant differences in response distributions between the two DSS tools was found in all but one question (Q11). Finally, Q13 was observed to have the most drastic shift in responses (64% rating the Baseline DSS Slightly Effective to 64% rating the Advanced DSS Extremely Effective). This result suggests that the aspects of the DSS prototypes that were designs were successfully validated in fulfilling the combination



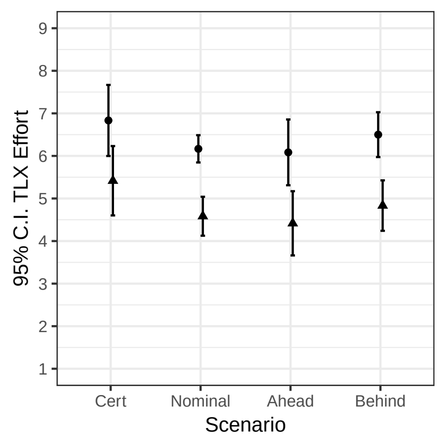

(a) TLX - Mental



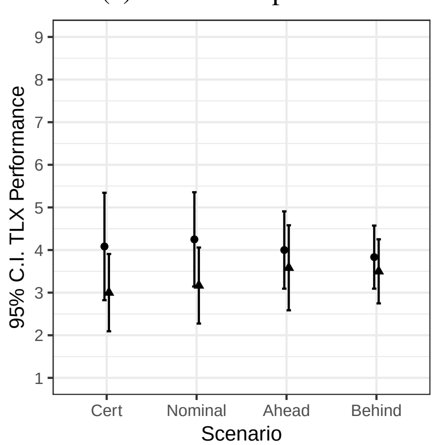

(b) Legend



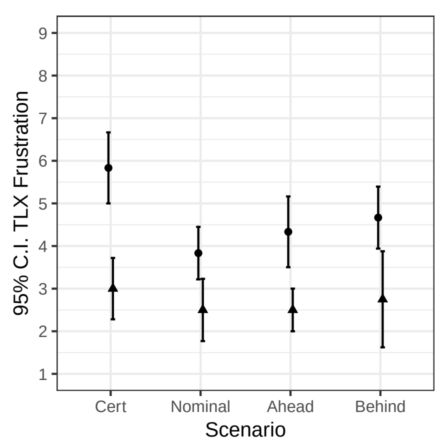

(c) TLX - Temporal




(d) TLX - Effort




(e) TLX - Performance




(f) TLX - Frustration

Figure 6.32: TLX subscale 95% confidence interval scores per DSS and scenario

Table 6.23: Cognitive support assessment heat map of responses with associated Kruskal-Wallis test results.

| ID | Question | Baseline Tool | | | | | Advanced Tool | | | | | Kruskal-Wallis chi-squared | p-value |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Not Effective at All | Slightly Effective | Somewhat Effective | Very Effective | Extremely Effective | Not Effective at All | Slightly Effective | Somewhat Effective | Very Effective | Extremely Effective | | |
| Q1 | Supporting communication and coordination among EVA operators (MCC, IV, and EV crew) | 0.0 | 0.0 | 33.3 | 63.9 | 2.8 | 0.0 | 0.0 | 2.8 | 47.2 | 50.0 | 24.79 | 6.40E-07 |
| Q2 | Thinking specifically with regard to potential timeline alterations, supporting communication and coordination among EVA operators (MCC, IV, and EV crew) | 0.0 | 33.3 | 52.8 | 8.3 | 5.6 | 0.0 | 2.8 | 19.4 | 55.6 | 22.2 | 26.74 | 2.32E-07 |
| Q3 | Maintaining awareness of tasks being performed by the EV crew | 0.0 | 19.4 | 25.0 | 52.8 | 2.8 | 0.0 | 2.8 | 19.4 | 33.3 | 44.4 | 13.62 | 2.24E-04 |
| Q4 | Maintaining awareness of upcoming tasks to be performed by the EV crew | 0.0 | 22.2 | 22.2 | 55.6 | 0.0 | 0.0 | 0.0 | 11.1 | 50.0 | 38.9 | 20.90 | 4.84E-06 |
| Q5 | Identifying where EV crew members are in the EVA timeline | 0.0 | 11.1 | 47.2 | 38.9 | 2.8 | 0.0 | 0.0 | 13.9 | 66.7 | 19.4 | 17.29 | 3.20E-05 |
| Q6 | Identifying which segments of the EVA deviated from the planned timeline, if any | 5.6 | 47.2 | 30.6 | 11.1 | 5.6 | 0.0 | 2.8 | 41.7 | 41.7 | 13.9 | 20.48 | 6.04E-06 |
| Q7 | Identifying  which tasks are most critical | 2.8 | 2.8 | 38.9 | 55.6 | 0.0 | 0.0 | 0.0 | 8.3 | 47.2 | 44.4 | 23.79 | 1.07E-06 |
| Q8 | Assessing implications of delays in EV crew task execution | 17.1 | 40.0 | 40.0 | 0.0 | 2.9 | 0.0 | 2.9 | 25.7 | 45.7 | 25.7 | 33.31 | 7.85E-09 |
| Q9 | Supporting effective planning of EVA timeline for each EV crew member | 0.0 | 27.8 | 47.2 | 22.2 | 2.8 | 0.0 | 0.0 | 27.8 | 50.0 | 22.2 | 20.34 | 6.48E-06 |
| Q10 | Providing support for prioritizing your tasks as an IV operator | 5.6 | 22.2 | 52.8 | 16.7 | 2.8 | 0.0 | 0.0 | 5.6 | 63.9 | 30.6 | 37.58 | 8.79E-10 |
| Q11 | Identifying what are the most limiting consumables for each EV crew member | 0.0 | 16.7 | 11.1 | 52.8 | 19.4 | 0.0 | 2.8 | 27.8 | 25.0 | 44.4 | 2.40 | 0.1214 |
| Q12 | Identifying detrimental trends in the EV crew telemetry data | 0.0 | 8.3 | 22.2 | 58.3 | 11.1 | 0.0 | 0.0 | 11.1 | 58.3 | 30.6 | 6.80 | 9.13E-03 |
| Q13 | Assessing the timeline margin available, relating the estimated end of the EVA timeline with the most current limiting consumable | 5.6 | 63.9 | 19.4 | 11.1 | 0.0 | 0.0 | 0.0 | 11.1 | 25.0 | 63.9 | 49.34 | 2.16E-12 |
| Q14 | Identifying potential timeline alterations | 16.7 | 41.7 | 30.6 | 11.1 | 0.0 | 0.0 | 5.6 | 36.1 | 44.4 | 13.9 | 27.38 | 1.67E-07 |
| Q15 | Supporting effective alteration of EVA timeline | 16.7 | 41.7 | 27.8 | 8.3 | 5.6 | 0.0 | 8.6 | 34.3 | 40.0 | 17.1 | 18.40 | 1.79E-05 |

of TTA-28 and LSS-22 requirements.

*Interaction Assessment*

After completing each experimental session (either certification or run session) with each DSS tool, the participants were asked to assess their overall interaction with the DSS. Participants were asked to rate DSS characteristics using a modified Cooper-Harper scale which prompted a series of Yes/No questions to arrive at a final overall assessment. Figure 6.33 shows the final scores for each participant. The lines connecting each response indicates the direction of assessment from each session and DSS tool. Some interesting trends include the spread of responses within the Baseline DSS configuration. Specifically, five of the subjects rated the Baseline worst in the after completing all testing scenarios as compared to their Certification scenario, three participants remained constant and four rated the Baseline more favorable once the testing scenarios were completed. This spread of responses might indicate a 'settling effect' of the participants becoming comfortable with the simulation environment and tool. The Advanced DSS exhibited much less variability in responses with the majority of participants deeming the Advanced DSS acceptable with only one participant signifying deficiencies warrant improvement. A Kruskal-Wallis test confirmed statistical significance in the different of response distributions between the two DSS tools for their post-run responses ($\chi^2 = 9, p = 0.003$).

### 6.1.3 Integrated Summary of Results

Table 6.25 shows a compiled summary of the Spartan Laboratory experiment results. Across nearly all variables, a significant difference was observed between the two DSS tools. Among approximately half of the measured variables, Scenario played a marginal to significant role in overall performance. Interestingly, DSS Order impacted some variables while not influencing others, and as expected Scenario Order played little to no significant impact in performance. Where applicable, other independent factors were used to exam-

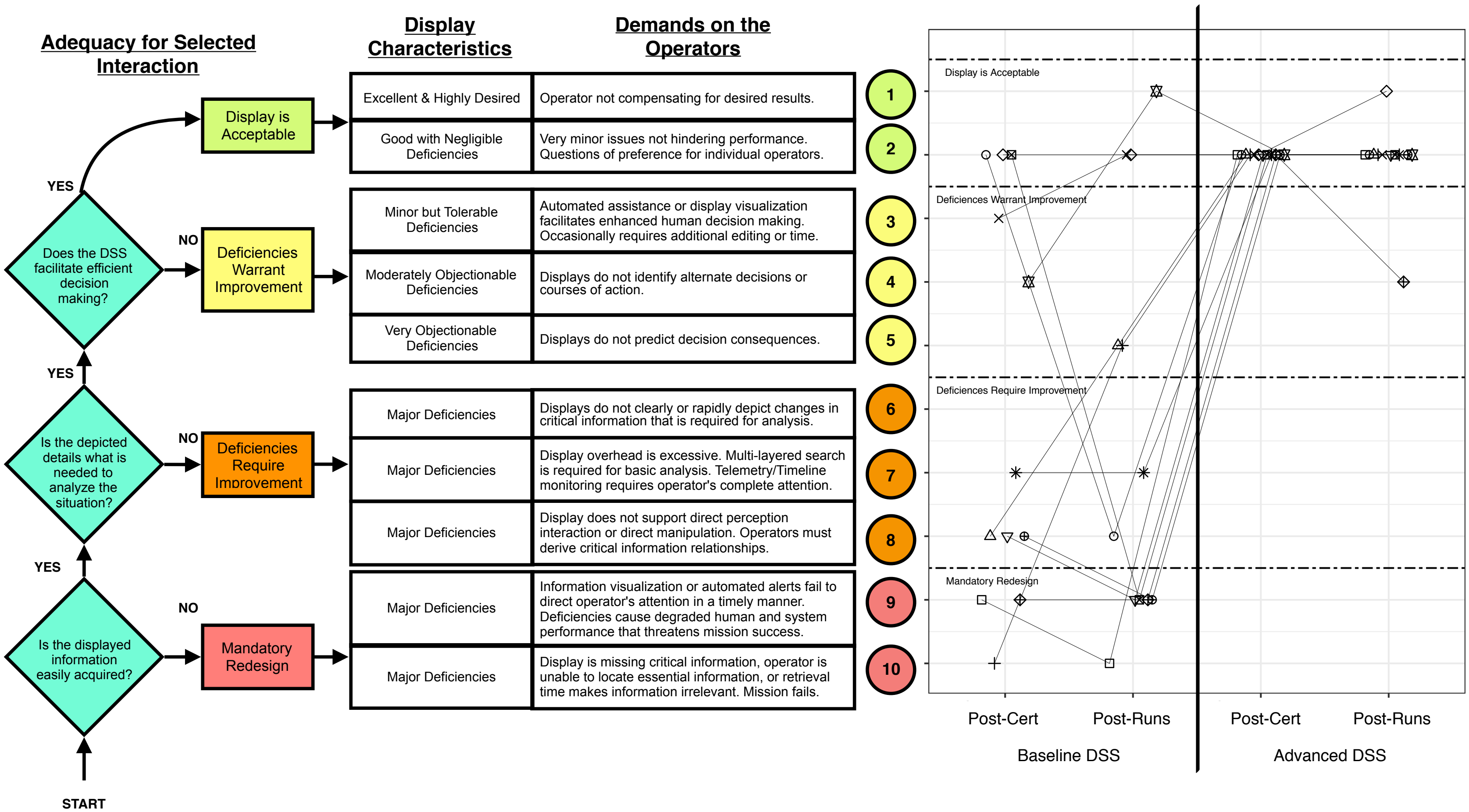



Figure 6.33: Interaction assessment scores. Note each unique symbol is representative of each participant.

ine tendencies in operator performance. When the operator performed (at specific probe points) timeline Margin and Minutes Behind calculations had a significant impact on performance. Additionally, differences in the communication interactions between the EV crew were also observed.

## 6.2 Discussion

This experiment attempted to examine the effectiveness of various DSS configurations specifically designed to support an IV operator within an envisioned EVA environment. Specifically, the Spartan Laboratory experiment sought to examine both DSS designs with respect to the design requirements leveraged to create the prototypes as well as comparatively examine the advantages and disadvantages of the designs. The following sections first relate the designs to their respective design requirements and then compare between the benefits of the DSS designs. An emphasis in this discussion is made between the designs and design requirements to begin the process of establishing acceptable standards in the future work domain. I do not assert that each requirement was fully satisfied by these prototype designs. However, I do believe the prototype designs, coupled with these demonstrated metrics of performance and feedback help promote continued requirements specificity and success criteria specification.

### 6.2.1 Q1: How effective was the Baseline DSS at satisfying its design requirements?

As reiterated in Table 6.24 from Chapter 5, the Baseline DSS relied heavily upon the IV operator to provide many of the executive functioning and critical thinking required by the prioritized design requirements. While participants rated their overall workload high, the IV operators were still able to perform their job to varying degrees of success. The remainder of this section discusses the specific implications the test results have on each DSS design requirement and then aggregate summary perspectives are provided.

- **LSS-1**: Basic alerting features, that mimic present-day systems, somewhat successfully captured the attention of the IV operator (across all test scenario conditions,

Table 6.24: Baseline DSS design elements with associated design requirements.

| | | Requirements (ID) | |
|---|---|---|---|
| DSS | System Elements | LSS | TTA |
| Baseline | **Life Support System** | 1, 5, 13, 11 | |
| | LSS-Numeric Display | 8, 25 | |
| | LSS-Graphical Display | 2 | |
| | **Timeline Artifacts** | | 10, 13, 16 |
| | Summary Timeline | | |
| | Detailed Procedures | | |
| | Flight Notes | | |
| | **IV Operator w/Communication System** | **22,** 28, 34, 36 | 1, 6, 8, 19, **28,** 32, 35, 39, 41, 47 |

Table 6.25: Integrated summary of Spartan Laboratory results.

| | | Independent Factors | | | | |
|---|---|---|---|---|---|---|
| **Work Function** | **Variable** | **DSS Tool** | **DSS Order** | **Scenario** | **Scenario Order** | ***Other*** |
| Life Support System Management | Numeric/Alert Event Recognition | S | M | N.S | N.S | N.A |
| | Trend Event Recognition | N.S* | N.S | N.S | N.S | N.A |
| | Trend Event Response Time | N.S | N.S | N.S | S | N.A |
| Timeline Management | Step Coverage | S | N.S | N.S | M | EV Crew - S |
| | IV Communication Behavior | S | N.S | M | N.S | EV Crew - S |
| | Timeline Margin Calculation | M | M | S | N.S | Probe - S |
| | Minutes Behind Calculation | S | S | M | N.S | Probe - S |
| | Confidence Interval Estimate | S | N.S | S | N.S | Probe - S |
| | Time to Complete Margin Calculation ($TTC_{Margin}$) | S | S | N.S | N.S | N.A |
| | Time to Complete Min. Behind Calculation ($TTC_{MinB}$) | S | S | N.S | N.S | N.A |
| Communication Management | IV to MCC Prompt Response Time | S | N.S | M | N.S | N.A |
| *Overall DSS Prototype Assessments* | Operator Proficiency Rating | S | N.A | S | N.A | Rater - S |
| | NASA Task Load Index (TLX) | S | N.S | N.S | N.S | N.A |
| | Cogntive Support Assessment | S | N.A | N.A | N.A | N.A |
| | Interaction Assessment | S | N.A | N.A | N.A | N.A |

| Level of Significance | | | |
|---|---|---|---|
| **Significant** | **Marginal** | **No Difference** | **Not Applicable** |
| S | M | N.S | N.A |

*There was a significant difference in the # of surplus trend events acknowledged

60% of numeric events on average were acknowledged by IV operators). Furthermore, these alerts only consisted of hard engineering limits as opposed to typical operating limits and this simulation did not assume the IV operators had any prior experience or knowledge of the variables and their respective limits.

- **LSS-2**: Trend graphs, that mimic present-day systems, for the most part successfully captured the attention of the IV operator (across all test scenario conditions, 91% of trend events on average were acknowledged by IV operators). Furthermore, these alerts only consisted of hard engineering limits as opposed to typical operating limits and this simulation did not assume the IV operators had any prior experience or knowledge of the variables and their respective limits.

- **LSS-5**: The association of variables plays a key role in LSS data synthesis. In the Baseline DSS design, all raw data were presented at the same level within the displays (e.g. the full suite of raw data in numerical and graphical form existed in a single view for consumption). No association support was provided by the Baseline DSS, leaving the IV operator to associate data. While this simulation did not explicitly examine this associative property of the display, it did provide one example of how to begin to consider the ramifications surrounding this requirement.

- **LSS-8**: The Baseline DSS provided a description of the discrete modes currently considered regarding the spacesuit. No vehicle system states were incorporated, nor did the simulation explicitly examine this particular aspect of the LSS data synthesis process. Again, this prototype design helps begin the discussion regarding how to best visualize these mechanical configurations as future systems become online.

- **LSS-11**: The Baseline DSS provided no associative capabilities regarding expected values associated with periods of the timeline. The IV operator is left to provide this capability based on prior knowledge and experience, which was not explicitly tested in this test campaign. This prototype design does help expose opportunities for future development in associating LSS values with timeline components.

- **LSS-13**: While alerts were triggered in these testing scenarios, the incorporation of fault trees was not fully implemented. However, it is important to note that the domain demands that simply acknowledging the alert is sufficient and that scrutiny of those events is expected. How to best incorporate the ability to examine confirming cues and fault tree analyses into a useful prototype design is an area of future research.

- **LSS-22**: The Baseline DSS design does provide the minimum set of information bits to make this association. However, as shown in Figure 4.2, the IV operator must pull from a variety of sources to achieve this system state understanding. The simulation results indicate this calculation as performed using the Baseline DSS is prone to error and is in all likelihood, not a sustainable way to supporting future operations.

- **LSS-25**: The forecast of consumables was provided directly by the Baseline DSS. Under present-day operations, the time estimates are based on usage-rate estimates only. However, usage rates are prone to shift rapidly and may not provide an appropriate long term estimate of remaining consumables (hence the two different usage rate averages performed on the limiting consumables). The IV operator was successful at referencing this value throughout EVA execution. Opportunities do exist to make this estimate more accurate and appropriate for timelines as they are being performed.

- **LSS-28**: Ambiguity can arise during execution when systems approach operational and engineering constraints and how that relates to timeline components. The Baseline DSS as designed does not incorporate any historical data to help better estimate of LSS performance as it relates to timeline components. Present-day operations rely on historical experience, retained within the flight control team to know the nuances of particular spacesuit system performance tendencies and how astronauts typically tend to perform on particular tasks.

- **LSS-34**: The Baseline DSS provides the IV operator a binary yes or not to being aware of whether the LSS is maintaining crew and vehicle safety (based on what it can measure and sense). Much more investigation must be given to how to support transitioning between nominal and off-nominal LSS performance to help dictate what desired timeline alterations must be implemented.

- **LSS-36**: The Baseline DSS provided the IV operator a moment-by-moment snapshot and aggregate vantage point of LSS performance. However, there are no established processes or capabilities in place to establish whether or not LSS capability can meet timeline objectives. The incorporation of historical performance data as well as more explicit linkages to the actual vs. as-planned performance progress is likely to yield more support capability.

- **TTA-1**: The Baseline DSS only provided the planned timeline as a reference. The IV operator was responsible for manually estimating timeline progress. On average, across all scenario conditions, the IV operator estimated the EV crew to be $\approx 2.5$ minutes more ahead of schedule than they actually were. That estimate jumps to $\approx 9$ minutes when asked to perform an estimate of timeline progress away from clear transition periods of within the timeline. These results can have profound implications regarding timeline design and making appropriate tactical decisions during execution, particularly when attempting to maximize the utility of time spend during EVA.

- **TTA-6**: The communication between EV and IV crew members mimicked present-day expectations. The IV operator relied upon feedback and the dialog provided by EV crew to obtain task verification and gauge execution progress. The DSS itself did not synthesize any audio input from that dialog.

- **TTA-8**: The Baseline DSS timeline contained some geospatial information but primarily contained task and timing detail. The IV operator was responsible for mapping the actual progress in relation to this reference information. In addition to estimating timeline progress, the IV operator needed to track each individual step of each EV crew's timeline. On average, $\approx 74\%$ of high priority procedure steps were explicitly discussed with the EV crew as they were performed. Those steps that were missed will likely force reviews or MCC prompts via time-delayed communication to ensure comprehensive coverage in future missions.

- **TTA-10**: In the current form, the timeline only provide text descriptions to support operations. Furthermore, the IV operator was not expected to supplement that detail with prior knowledge or experience. While most descriptions are usually described via text, the addition of annotated imagery or even video descriptions will impose new timeline elements that paper products may not appropriately handle.
- **TTA-13**: This simulation incorporated simplified success criteria for each and every step of the timeline. Furthermore, the EV crew were scripted to have final authority over matters of completeness of any particular step. But in future operations, timeline objectives may not have such clear cut success criteria.
- **TTA-16**: The Baseline DSS timeline incorporated basic hazards, cautions and warning information embedded within the artifacts. The IV was responsible for relaying that information in a timely manner to the EV crew. Future work will need to begin incorporating a host of system and vehicle related information to make the IV/EV crew more aware of the potential hazards of their surroundings.
- **TTA-19**: In terms of helping estimating overall timeline progress, the IV was responsible for manually making that assessment. In an ideal world, 100% of the steps within the timeline would be covered as well as a Minutes Behind estimate would contain no error.], but as this simulation demonstrated, that is not the case. Other than enhanced training of the IV operator, the Baseline DSS offers few mechanisms to reduce these unwanted biases.
- **TTA-28**: As one of the critical requirements addressed in this thesis, the Baseline DSS provides somewhat adequate support to an IV operator charged with calculating an overall timeline margin value. On average, the IV operator margin error was $< 1$ minute. However, the 95% C.I. boundary surrounding that estimate was $\approx 3$ minutes. Finally, the IV operator took on average $> 1.6$ minutes to complete the calculation. The results indicate that while the Baseline DSS *can* support the estimate of timeline margin, it is likely unsustainable for future operations.
- **TTA-32**: Having an accurate estimate of timeline margin is important, but it is also important to work within acceptable factors of safety. The Baseline DSS offers no immediate mechanisms to know how close systems are to their limits or how close the timeline is to becoming unfeasible based on LSS constraints. Supporting more robust examinations of alternative timeline solutions is a needed area of future work that the Baseline DSS design would require significant redesigns to accommodate.
- **TTA-35**: Again, the assumption with this simulation was that the EV crew had final authority over whether a task was completed (based on their scripts). The intent here is addressing the ambiguous challenge of actually verifying and validating each incremental step of the timeline throughout execution.

- **TTA-39**: The Baseline DSS include no information or considerations regarding criteria to maintain crew or vehicle safety. While the timeline is designed with this criteria in mind, a challenge of future work will be to more explicitly make this safety criteria apparent to operators when the crew deviation from the nominal timeline.

- **TTA-41**: The dialog promoted during this simulation was largely 'on-time.' In other words, on average the Baseline DSS promoted dialog regarding timeline discussion to be $\approx 50\%$ on-time or $\approx 26\%$ proactive. Furthermore, all content worth relaying was contained on the timeline documents themselves. The Baseline DSS overall serves as a minimum set of details as this volume of information will likely grow in the future. (See Chapter 5 for examples from the Staged world observations).

- **TTA-47**: The Baseline DSS represented a simplistic view of everything that needed to be performed during the EVA, as it was explicity specified in the timeline. This is a direct results of basic, and direct timeline objectives. No mention of objective prioritization or mission level constraints were imposed in this design or simulated. This type of integration is likely only to grow as more systems are added to the domain and Earth-based personnel attempt to more closely influence EVA execution.

*Baseline DSS Requirements Summary*

The participants successfully utilized LSS Focus Area to catch deviations (both numeric and graphical events) and provided timely responses to those events. Furthermore, the Baseline DSS was rated predominantly 'Somewhat' to 'Very' Effective at conveying the limiting consumable and detrimental trends in the telemetry data. The specific LSS requirements incorporated into the Baseline DSS design that pertain to the alerting (LSS-1,2) and sets of observations (LSS-5,8,11) provide an appropriate starting point to start exploring more complicated LSS visual displays. For example, LSS-13 emphasizes the need to help identify confirming cues as a way to navigate and address fault tree analyses. This spartan laboratory did not explicitly incorporate fault tree analyses into the simulation. However, the raw data included in the displays are a necessary component of expanding upon that aspect of life support system management. All but three participants rated the Baseline DSS as having overall deficiencies that warrant, require, or should be mandatory for redesign. Comments from participants included: *"Displayed information is relevant but it's very difficult to keep up with it in a timely manner and slowed down my perfor-*

*mance tremendously."* and *"It was difficult to keep looking down at the tasks in front of me, to the left side for the timeline estimates, and scanning the vital graphs and data summary. Dividing my attention between 6 different sources contributed to significantly slower reaction time for events and slower communication of tasks to EV1 and EV2."* Future work will need to be dedicated to how best to incorporate even more information dense LSS displays to address the remaining LSS requirements specified in Appendix A.2.

The participants successfully utilized Timeline Management Focus Area to track EV crew progress and estimate both overall timeline margin and minute behind estimates. However, excessive effort was dedicated to manually tracking both EV crew progress and the subsequent calculations required to maintain awareness of overall timeline progress. The disparate pieces of timeline artifacts were somewhat distracting as captured by one participant's comment: *"Flipping back and forth between pages was difficult. It was very cumbersome to perform the calculations, which took away valuable time and focus from other IV tasks."* The participants did successfully generate timeline margin and minute behind estimates most of the time, but as the various timeline management variables results show, the variability surrounding those estimates were not negligible. Additionally, the tendency to produce error on the side of less conservative estimates was common. As a few participants commented, the ability to both listen attentively to crew while performing calculations or addressing other components of the workstation can be difficult to perform simultaneously.

Overall, the Baseline DSS provided enough raw materials to enable the IV operator to perform their work. However, the resulting demands on operator workload and performance are likely not sustainable for future missions. To reiterate, this Spartan Laboratory specifically targeted through DSS designs ways to bridging the capabilities of life support system and timeline management (as captured in LSS-22 and TTA-28). When specifically asked how effective the Baseline DSS was in supporting this synthesize process (e.g. generating a Timeline Margin value), 64% of responses were rated as only 'Slightly' Effective, indicating there is still plenty of room for improvement and design refinement.

### 6.2.2 Q1: How effective was the Advanced DSS at satisfying its design requirements?

As reiterated in Table 6.26 as defined in Chapter 5, the Advanced DSS represents a first step towards re-imaging how the IV operator support system might someday support EVA operations. As such, a computerized version of the the EVA timeline was constructed to take on many of the cognitive support/information relationship requirements previously left to the IV operator to explicitly manage. The remainder of this section discusses the specific implications the test results have on each DSS design requirement and then aggregate summary perspectives are provided.

Table 6.26: Baseline DSS design elements with associated design requirements.

| | | Requirements (ID) | |
|---|---|---|---|
| DSS | System Elements | LSS | TTA |
| Advanced | **Life Support System** | 1, 5, 13, 11 | |
| | LSS-Graphical Display | 2 | |
| | **Timeline Artifacts** | **22** | 1, 6, 8, 10, 13, 16, 19, **28,** 32, 35, 39 |
| | Detailed Procedures w/Integrated LSS Numeric Display | 8, 25 | |
| | **IV Operator w/Communication System** | 28, 34, 36 | 41, 47 |

- **LSS-1**: The new alerting feature somewhat successfully captured the attention of the IV operator (across all test scenario conditions, 77% of numeric events on average were acknowledged by IV operators). While simplistic, this alerting feature is only a first towards a much sophisticated caution and warning system. Referencing other domains such as air traffic control or health care will prove useful before attempting to design such alerting systems for EVA operations.
- **LSS-2**: Trend graphs, that mimic present-day systems, for the most part successfully captured the attention of the IV operator. Across all test scenario conditions, 94% of trend events on average were acknowledged by IV operators. Furthermore, these alerts only consisted of hard engineering limits as opposed to typical operating limits and this simulation did not assume the IV operators had any prior experience or knowledge of the variables and their respective limits. Advanced data analytics and machine learning algorithms offer the potential to revolutionize how LSS data is handled and processed.

- **LSS-5**: The association of variables plays a key role in LSS data synthesis. In the Advanced DSS design, all numeric raw data were hidden behind the integrated timeline management tool. Only the limiting consumable and alert button were visible to the IV operator at any given time alongside the same graphical displays. While this simulation did not explicitly examine this associative property of the LSS display, this prototype did provide one example of how to begin to consider the ramifications surrounding this requirement and how LSS data might be layered to yield more lower level raw sensor data in appropriate situations.

- **LSS-8**: The Advanced DSS completely omitted system state information from the IV operator and managed that internally. While no vehicle system state anomalies were incorporated, this approach indicates one pathway forward to pursuing a 'dark cockpit' approach to IV workstation design. Again, this prototype design helps begin the discussion regarding how to best visualize these mechanical configurations as future systems become online.

- **LSS-11**: The Advanced DSS provided no associative capabilities regarding expected values associated with periods of the timeline. The IV operator is still left to provide this capability based on prior knowledge and experience, which was not explicitly tested in this test campaign. However, now that a digital representation of the timeline exists within the DSS, incorporating design features to satisfy this requirement are more tenable.

- **LSS-13**: While alerts were triggered in these testing scenarios, the incorporation of fault trees was not fully implemented. However, the Advanced DSS does now provide a platform pursuant to this requirement. How to best incorporate the ability to examine confirming cues and fault tree analyses into a useful prototype design is an area of future research.

- **LSS-22**: The Advanced DSS design provides an integrated approach to managing the limiting consumables. As shown in Figure 4.12, the IV operator, by simply tracking timeline progress, can access the limiting consumable and underlying constraint it imposes on the remainder of the timeline. This design offers one approach to satisfying this requirement that appears to be sustainable for future operations.

- **LSS-25**: The forecast of consumables was provided directly by the Advanced DSS. Under present-day operations, the time estimates are based on usage-rate estimates only. However, usage rates are prone to shift rapidly and may not provide an appropriate long term estimate of remaining consumables (hence the two different usage rate averages performed on the limiting consumables). The IV operator was successful at referencing this value throughout EVA execution. Opportunities still do exist to make this estimate more accurate and appropriate for timelines as they are being performed by accessing historical databases of prior trends to refine forecast estimates.

- **LSS-28**: Ambiguity can arise during execution when systems approach operational and engineering constraints and how that relates to timeline components. The Advanced DSS does not currently incorporate any historical data to help better estimate of LSS performance as it relates to timeline components. However, now that the design can internally track both LSS and timeline progress, opportunities now exist in the software architecture to address this requirement.

- **LSS-34**: The Advanced DSS currently provides the IV operator a binary yes or not to being aware of whether the LSS is maintaining crew and vehicle safety (based on what it can measure and sense). Alongside the previously discusses requirements regarding fault tree analyses and historical regression, future research must be given to how to support transitioning between nominal and off-nominal LSS performance to help dictate what and when desired timeline alterations must be implemented.

- **LSS-36**: The Advanced DSS provided the IV operator a moment-by-moment snapshot and aggregate vantage point of LSS performance with a synthesized view of timeline progress. While the current version does not contain relations to timeline objectives, opportunities to explore how those connections can now be made to link data between the timeline and LSS. The incorporation of historical performance data as well as more explicit linkages to the actual vs. as-planned performance progress is likely to yield more support capability.

- **TTA-1**: The Advanced DSS provided both a planned timeline and internally tracked an as-performed timeline. The IV operator was responsible for 'checking-off' timeline steps as they were completed. Based on this action, on average, across all scenario conditions, the IV operator estimated the EV crew to be $< 10$ seconds more ahead of schedule than they actually were. That estimate jumps to $\approx 3$ minutes when asked to perform an estimate of timeline progress away from clear transition periods of within the timeline. The IV operators demonstrated an overall more confident and accurate estimate of timeline progress. Furthermore, the drifts that did occur in this estimate can be further tailored based on the internal logic assumptions made, thereby providing a control mechanism not afforded by the Baseline DSS design.

- **TTA-6**: The communication between EV and IV crew members mimicked present-day expectations. The IV operator relied upon feedback and the dialog provided by EV crew to obtain task verification and gauge execution progress. The DSS itself did not synthesize any audio input from that dialog. However, now that the Advanced DSS now knows what to expect crew to be performing, the incorporation of natural language synthesis is now more tenable.

- **TTA-8**: The Advanced DSS timeline contained some geospatial information but primarily contained task and timing detail. Using the digital timeline, the IV operator on average explicitly covered $\approx 86\%$ of high priority procedure steps with the EV crew as they were performed. Those steps that were missed will likely force reviews or MCC prompts via time-delayed communication to ensure comprehensive coverage in future missions. While not implemented in this version of the prototype, the Advanced DSS now can implement reminders to ensure step coverage during execution.

- **TTA-10**: In the current form, the timeline only provide text descriptions to support operations. Furthermore, the IV operator was not expected to supplement that detail with prior knowledge or experience. While most descriptions are usually described via text, the addition of annotated imagery or even video descriptions are not more readily able to be incorporated into the digital timeline interface.

- **TTA-13**: This simulation incorporated simplified success criteria for each and every step of the timeline. Furthermore, the EV crew were scripted to have final authority over matters of completeness of any particular step. But in future operations, timeline objectives may not have such clear cut success criteria. The Advanced DSS now offers a way to incorporate multi-level success criteria or offer alternative suggests based on the situation to promote continued timeline execution.

- **TTA-16**: The Advanced DSS timeline incorporated basic hazards, cautions and warning information embedded within the artifacts. The IV was responsible for relaying that information in a timely manner to the EV crew. Future work will need to begin incorporating a host of system and vehicle related information to make the IV/EV crew more aware of the potential hazards of their surroundings. A digital timeline helps provide access points and references to make the management of this extra data more tenable.

- **TTA-19**: In terms of helping estimating overall timeline progress, the IV was responsible for working with the Advanced DSS to generate an assessment. In an ideal world, 100% of the steps within the timeline would be covered as well as a Minutes Behind estimate would contain no error, but as this simulation demonstrated, that is not the case. The Advanced DSS not only automatically generates progress estimates, the digital platform can now be expanded to include reminder and checklist material to ensure the IV operator covers all necessary details with the EV during execution to ensure mission success.

- **TTA-28**: As one of the critical requirements addressed in this thesis, the Advanced DSS provides a convincing level of success supporting an IV operator charged with calculating an overall timeline margin value. On average, the IV operator margin error was $\approx 2.7$ minutes (in a conservative sense). The 95% C.I. boundary surrounding that estimate was $\approx 1$ minute, indicating a consistent estimate. Finally, the IV operator took on average $< 22$ seconds to complete the calculation. The results indicate that the Advanced DSS *can* support the estimate of timeline margin, in a meaningful and sustainable way for future operations.

- **TTA-32**: Having an accurate estimate of timeline margin is important, but it is also important to work within acceptable factors of safety. The Baseline DSS offers no immediate mechanisms to know how close systems are to their limits or how close the timeline is to becoming unfeasible based on LSS constraints. Supporting more robust examinations of alternative timeline solutions is a needed area of future work that the Baseline DSS design would require significant redesigns to accommodate.

- **TTA-35**: Again, the assumption with this simulation was that the EV crew had final authority over whether a task was completed (based on their scripts). The intent here is addressing the ambiguous challenge of actually verifying and validating each incremental step of the timeline throughout execution. The digital timeline now provides a potential platform to support satisfying this requirement.

- **TTA-39**: The Advanced DSS included no information or considerations regarding criteria to maintain crew or vehicle safety. While the timeline is designed with this criteria in mind, a challenge of future work will be to more explicitly make this safety criteria apparent to operators when the crew deviation from the nominal timeline. When crew deviate from the timeline, the Advanced DSS will not only know that is occurring, but also potentially be capable of providing useful information to maintain crew and vehicle safety.

- **TTA-41**: The dialog promoted during this simulation was largely 'on-time.' In other words, on average the Baseline DSS promoted dialog regarding timeline discussion to be $\approx 58\%$ on-time or $\approx 21\%$ proactive. Furthermore, all content worth relaying was contained within the digital timeline. The Advanced DSS serves as a minimum set of details as this volume of information will likely grow in the future. (See Chapter 5 for examples from the Staged world observations).

- **TTA-47**: The Advanced DSS represented a simplistic view of everything that needed to be performed during the EVA, as it was explicitly specified in the timeline. This is a direct results of basic, and direct timeline objectives. No mention of objective prioritization or mission level constraints were imposed in this design or simulated. This type of integration is likely only to grow as more systems are added to the domain and Earth-based personnel attempt to more closely influence EVA execution. Again, the Advanced DSS provides a digital platform to begin exploring solutions to satisfy this requirement

*Advanced DSS Requirements Summary*

The participants successfully utilized LSS Focus Area to catch deviations (both numeric and trend) and timely responses to those events were registered. The Advanced DSS was rated predominantly 'Very', and 'Extremely' Effective at conveying the limiting consumable and detrimental trends in the telemetry data. The numeric LSS displays were simplified so that only the highest level pertinent numeric information was viewable. However, as the LSS requirements suggest, a host of more detailed information and content will need to be support in future designs.

The participants successfully utilized the new Timeline Management display to track

EV crew progress and as a consequence produce accurate estimates of timeline margin and minute behind. By simply 'clicking-off' steps as they were completed, the IV operator could closely track EV crew progress without the overhead of performing mental math calculations. Participants commented this new way of working was much improved over the paper-based tools.

Overall, the Advanced DSS demonstrated utility in supporting the IV operator conduct EVA operations. Temporal deviations were quantified and linked to life support consumable states as a first step towards the DSS providing higher level systems state awareness and support. When specifically asked how effective the Advanced DSS was in supporting this synthesize process (e.g. generating a Timeline Margin value), 64% of responses were rated as only 'Slightly' Effective, indicating there is still plenty of room for improvement and design refinement. The Advanced DSS provides a grounded example of how to begin approaching the myriad of challenges yet to be address in the full TTA requirements list in Appendix A.2.

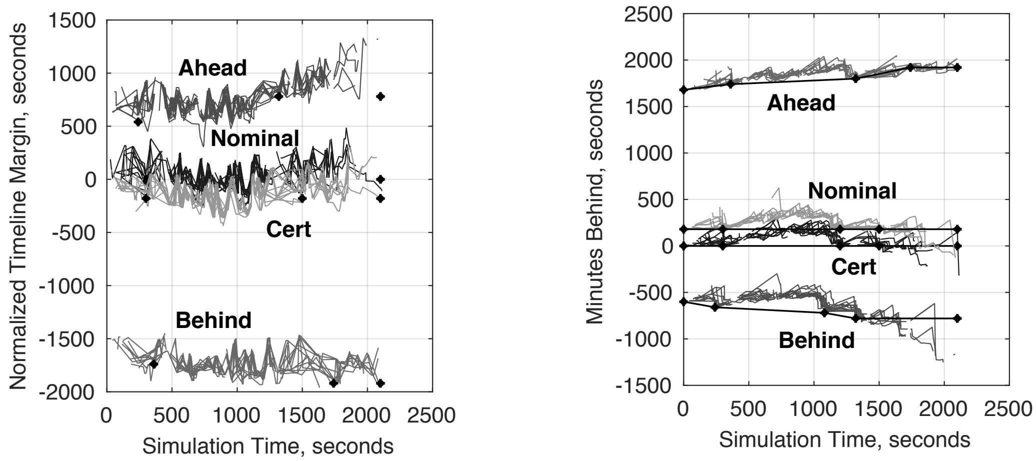
#### 6.2.3 Q2: How did operator performance compare between the two DSS prototype designs?

Nearly all measures of performance yielded statistically significant differences between prototype designs, in favor of the Advanced DSS design. Rather than restate the results section, I highlight here some of the more interesting comparisons between DSS designs and other influential factors on IV operator performance.

Central to this experiment was to examine how to synthesize timeline and life support system data in a meaningful way that was conducive to support EVA operations. Interestingly for the most critical EVA execution constraint (Timeline Margin), there was only a marginal difference in performance between the two DSS designs to accurately estimate its value. This result indicates two important aspects: 1) the Baseline DSS does provide enough discrete support capability to yield a reasonable margin estimate and 2) the Advanced DSS provides a multitude of other advantages other than direct computation of the margin value itself. When we examine the results further, the advantages of the Advanced are more clearly observed. In terms of accuracy and precision, the Advanced DSS produced more consistent estimates with less variability as compared to the Baseline. Variability was reduced by a factor of two by using the Advanced DSS, which means more consistent and reliable answers were produced throughout execution. When a calculation was performed can have an impact on the accuracy as demonstrated in this study. Clear transition points in the timeline promoted less Margin error for both designs, with the Advanced DSS producing less variable answers. Both systems also tended to produce more Margin error in the middle of a Station activity. As hypothesized, the farther away from a clear transition reference point in the planned timeline, the more opportunities for drift and error in Margin estimates there are.

Similar trends were exhibited for the Minutes Behind calculation between the two DSS designs, except the Advanced DSS demonstrated a significant advanced over the Baseline DSS. The drift in error becomes more apparent in this calculation, given that the IV operator performed this calculation more frequently (as shown in Figure 6.8). Of concern here though is that as the EV crew enter the longer duration (35 min) segment of Station 5 activity, the ability for the IV operator to accurately estimate crew location in the timeline declines. In fact, using both DSS systems, the IV operator tended to provide less conservative estimates of crew progress, in effect thinking the crew were more ahead of schedule than they actually were. If future missions are to promote flexibility in EVA timeline execution, close consideration must be paid to timeline designs that incorporate reference points so that reasonable estimates of crew progress can be calculated. The Baseline DSS design offers no obvious way to cope with this drift in Minutes Behind or Margin estimates. However, the Advance DSS can be recalibrated to product more conservative or less conservative estimates based on its internal distribution of the durations of each timeline step.

Marvin's ability to track the moment by moment EV crew progress provides a never before quantified vantage point of EVA crew progress, as shown in Figures 6.34a and 6.34b.




(a) Timeline Margin Tracking

(b) Timeline Minutes Behind Tracking

Figure 6.34: Marvin Timeline Tracking Data from the spartan laboratory simulations

The solid black lines and dots represent the simulated 'truth' data whereas each cluster of lines represent each participant, completing each simulation scenario. The data shown in these figures represent how the IV operator interacted with Marvin and the resultant Marvin estimates calculated to support EVA operation. The Margin values are normalized for demonstration purposes here. Never before has the EVA work domain had access to these temporal timeline progress measures other than performing periodic calculations by hand which can now have a profound impact on how future EVA timelines are executed.

Finally, the ability to produce these estimates 'on demand" are critical to promoting meaningful EVA support. That means being capable of providing an estimate at a moment's notice and not expending an unreasonable amount of time and effort to produce an estimate. Under this perspective, the Advanced DSS advantages become readily apparent. Not only does the Advanced DSS track each moment of EV crew activities, thereby producing updated estimates, the calculations occur instantaneously. The time to compute the timeline margin and minute behind estimates were reduced by nearly a factor of three. Instead of demanding 2 minutes of the IV operators time and attention (while also relying on users' mathematical capabilities), the IV operator can simply reference the display header for all pertinent information. This in turn frees the IV operator to more readily address EV crew conversation and system states without the overhead of data association and performing math calculations.

### 6.3 Spartan Laboratory Simulation Summary

> "These tools permit us to transform difficult tasks into ones that can be done by pattern matching, by the manipulation of simple physical systems, or by mental simulations of manipulations of simple physical systems. These tools are useful precisely because the cognitive processes required to manipulate them are not the computational processes accomplished by their manipulation. The computational constraints of the problem have been built into the physical structures of the tools (Hutchins, 1995, p. 171)."

This quote epitomizes the translation we aimed to accomplish for in the advanced tool. This chapter examined how two DSS designs could support EVA operations and how specific design features could integrate the intrinsic work domain computations within the 'software' structure without squandering the hierarchical task structure embedded within the paper products and the realistic volume of detail necessary to manage to execute EVA.

Also this work demonstrates the appropriate level of scrutiny that should be considered to developing useful EVA prototype designs by imposes a set of metrics by which we need to begin measuring to demonstrate successive design utility. For example, EVA flight controllers painstakingly examine each and every element of an EVA timeline throughout execution, therefore the Steps Coverage measure reflects and measures directly the IV operators ability validate the completion of each and every timeline step (Note that not all steps are covered, even when told to and trained to).

The point of this Spartan Laboratory setting was to specifically target these design features and explore their utility in a simplified, yet realistic context. The result of this effort is a more rich and complete description of the assumptions being made (and purposefully omitted) with respect to the new technologies and the environment within which they are being desired for. By fabricating these components, we promote constructive criticism to its short comings as a means to hopefully yield a more appropriate and realistic design solution for future EVA operations. The perspective of extensibility is key to this effort and making strides towards not only addressing and overcoming key challenges within the domain of interest, but also establish the necessary conditions form which new designs and capabilities can be built upon. This work represents a first step towards computational support of timeline tracking as a step towards constructing a whole suite of digital products dedicated to supporting future EVA operations.

# CHAPTER 7
# CONCLUSIONS & FUTURE WORK

## 7.1 Summary of Contributions

As the future of human spaceflight sends humans into deep-space, the demand for useful, comprehensive capabilities in future support systems will increase. For nearly all aspects of human spaceflight operations, such as human EVA, there will be a necessary transition of the wealth of support provided by mission control personnel to astronauts to leverage local knowledge to ensure mission success. Recognizing the magnitude of this shift and the implications it will potentially have on future operations, the contributions of this thesis advance the state of the art in several areas to meet these challenges.

First, this thesis demonstrations how cognitive systems engineering insight can be captured in a set of high level system design requirements, thereby making the content and utility of those insights accessible to both the CSE practioners and the broader systems engineering community. Existing CWA models are implemented and combined with a defined set of cognitive work and information relationship requirements so that a direct linkage can be made between research insights and resultant design requirements. More importantly, the CWA modeling process enabled both a broad and then a subsequently more targeted research focus so that meaningful avenues for development could be identified. All too often to design solutions supersede first addressing which specific aspects of work are worth investigating. This challenge is compounded by trying to design for a work domain that does not exist. As a result, this work emphasized in Chapter 5 that an approach that not only studies the existing domain, but also an envisioned staged world should be incorporated into the design process. It is hoped that the contributions and demonstration of simultaneously examination of both existing and future domain components are used during the conceptual design phase to help designers reveal and narrow the design space of potential technological solutions.

Second, this thesis demonstrates how a set of design requirements can be prioritized and applied to the development of prototype decision support system (DSS) design solutions. The value in generating requirements in Chapter 3 is that (1) the requirements appropriately capture the constraints and demands inherent to the work domain and (2) they can be objectively weighted and prioritized. The resultant prototype designs represent hypothesized design solutions to meet the prioritized requirements. As demonstrated, two prototype designs were generated: a Baseline DSS that reflected existing work domain artifacts, re-imaged for use in future EVA operations; an Advanced DSS incorporated novel design components to establish a first-of-a-kind digital management system for future EVA operations. For the first time, EVA work domain artifacts were designed in software that reflected both the content, form, and demands associated with EVA execution. Specifically, life support system consumable constraints were directly linked to timeline tracking information to yield necessary EVA execution metrics such as timeline margin and minute behind/ahead estimates. Additionally, not only are these mission critical elements explicitly incorporated into the prototype design, they are generated in a way that likely reflects the work practices of future intravehicular (IV) operators.

Finally, this thesis evaluated the resultant prototypes against the requirements to demonstrate both validity of the requirements and the verification of the design. The intent here is to first define what is required by the domain and hypothesis how new design solutions might be capable to promote desired capabilities specified by the requirements derived from the work in Chapter 3. This campaign established a suite of EVA-specific measures of performance and quantified the performance variability surrounding IV operator in a realistic simulation environment. This experimental approach offers a more precise description of the challenges surrounding the ability of the IV operator to adequately provide necessary work domain functions. The collectives demonstrated throughout Chapters 3 through 6 emphasize the critical pathway to yield effective design solutions stems from knowing what capabilities must be addressed. We live in an era where technology can provide a gamut of potentially useful capabilities, but when it comes to people performing work, the demands they face must be addressed in context with the purpose of supporting that work and the array of challenges associated with it.

## 7.2 Future Research Directions

### 7.2.1 Incorporating Additional CSE Research Perspectives

*Expand the scale and scope of scenarios for future EVA operations*

Opportunities for more detailed scenario development exist, now that this thesis provides a basic understanding of the EVA as work domain. Increasing the participation of more SMEs in the Spartan laboratory development process could yield a suite of other situations and problems worth evaluating prototype designs, particularly for off-nominal situations. For a review of scenario development techniques, see Carroll (2000); Roth et al. (2002); Torenvliet and Jamieson (2006) for useful examples.

*Explore the integration of new EVA systems as they become available for future operations*

NASA is currently developing new EVA systems to support future operations (i.e. space-suits, air locks, planetary surface hardware, etc.). As those systems become available, a concerted effort to incorporate these components within the scenario development process should be made. Incorporating methods such as the critical incident techniques (Smith et al., 1998; Alison et al., 2013) pertaining to these new EVA systems will be a useful approach to understanding the implications those systems will have on operations incorporating more EVA systems and hardware into the scenarios. An important aim of this effort would be to get these systems involved in the scenario evaluation process early in their respective design processes so that design decisions can be made to adequately shape overall system performance (as opposed to simply developing 'work-arounds' in the latter stages of development).

*Incorporate decision making theory into the decision support system development process*

This research was dedicated to first understanding the demands and constraints that exist within the EVA work domain as a precursor to supporting specific types of decisions or situations. Opportunities now exist to incorporate decision making theory such as naturalistic decision making (NDM) (Klein et al., 1993; Klein, 2008; Hoffman and Klein, 2017) and distributed decision making (Stanton et al., 2010; Woods and Sarter, 2010). These more targeted efforts can provide valuable structure to developing specific decision support system capabilities.

*Allowing insight into the envisioning process*

This thesis described over three years of time spent networking and examining the EVA work domain. The intent was to view the domain under the lens of how SMEs understand the tools they use and define their own work expectations. There is an inherent pressure for a project to produce technical solutions or solve some specific problem. Unfortunately, few studies demonstrate the value of the discovery process itself without spending a majority of their efforts describing their particular solutions. Solutions alone should not be the end result the envisioning process. The envisioning process starts with discovering the necessary work functions demanded by the domain. Through directed targeting of domain specific issues can potential solutions be hypothesized and explored. The CWA framework in particular provides support with this endeavor by providing a systematic approach to narrow in on specifics within a domain while still maintaining links to bigger picture elements. However, the ability to manage and prescribe opportunities to acquire domain insight for an envisioned future remains to be an area of continued research. As Grudin (1990) states below, technological solutions must always be cast within the context of understanding people and their attempts to successfully perform their work.

> "The capability for autonomous action will always be sharply limited by their ability to understand our needs and communicate with us. Their [computer] effectiveness as agents in the world will increase in step with their greater understanding of us. For that reason, work to develop an understanding of people will remain at the very heart of the computers development. It is the engine of change Grudin (1990, p. 267)."

### 7.2.2 Addressing and Enabling Additional Work Functions

*Expand the research focus to address the remainder of the design requirements*

The remaining requirements listed in Appendix A.2 still require attention. This research purposefully omitted areas of development regarding the management of LSS data. Given the descriptions of data synthesis process provided in Chapters 3 and 5, the opportunities for computational assistance (e.g. machine learning algorithms) are bountiful. These algorithms can be readily applied to monitor real-time trends and cross-correlate that information to a hysteresis of data to detect for abnormal trends with advanced alerting features. Furthermore, how future crew view and access this information will require attention. I suspect that functional schematics of the spacesuit subsystems provide a potentially useful starting point for displaying this data in meaningful ways to support troubleshooting, see Riley (1996); Riley et al. (1999); Riley (2000); Riley et al. (2002) for examples of how this perspective can be useful in practice.

*Expand the research focus to address the remainder of the EVA abstraction hierarchy elements*

The remainder of the AH elements require attention described in Chapter 3. This thesis focuses on only two out of the 11 generalized work functions for real-time EVA execution.

Similar research steps can now be taken to the remaining AH elements to reveal design considerations for support system development. Revisiting the design references missions (DRMs) already defined for human spaceflight operations would be a useful place to start synchronizing that content with the stated AH elements in this thesis. Specifically, EVA objectives must be distilled from these reference missions to more accurately map how those objectives will influence the remaining elements of the AH models (i.e. a 'Top-down' approach). At the same time, as more new systems become available, a 'bottom-up' approach can be simultaneously dedicated to addressing the lower level physical elements of the AH models.

*Expand the research focus to address the environment abstraction hierarchy*

The environment AH was developed in this thesis to emphasize the demands it imposes on EVA operations. Additional research should be dedicated to better incorporate environmental state information into the concepts of operations. How will future crew digest and synthesize this environmental information as a means to supporting their execution of EVA? Weather management as a whole is a new component of future EVA operations. Opportunities exist to leverage research in the military command and control and air traffic management domains to help develop this research aim (Scott et al., 2005; Ahlstrom, 2005; Nadav-Greenberg et al., 2008; Silva and Jensen, 2014; Ahlstrom, 2015).

*Contributing to the more general planning problem*

Planning in broader terms will require a host of new technologies and tools to support future operations. Particularly when we begin to separate plan execution and planning as a preparatory process. Numerous EVA flight controllers commented that an EVA timeline (plan) is only useful when the crew leave the airlock. Not only should research be dedicated to constructing necessary and efficient plans (Felker, 2012), the ability to restructure those plans must be considered. Furthermore, the integration of successive plans and the longer term 'mission-scale' planning process that future spaceflight will endure must address these perspectives.

Two EVA specific planning perspectives of are worth additional consideration: 1) the pre- and post- phases of EVA operations and 2) the integration of the geospatial information with timeline management. This thesis purposefully omitted examining the planning and post-EVA phases of operations, however, these phases present a host of unique challenges for future operations. How might new EVA timelines be generated across time-delayed communication and what support systems will successfully enable those processes? A useful starting point in understanding these phases of operations can be found in Connors et al. (1994); Schaber (2005); Bell et al. (2006); Gast and Moore (2011); Felker (2012). Secondly, the integration of geospatial planning information with EVA timeline artifacts will be required for future operation. Some preliminary work has already been performed to better estimate how terrain can impact crew energy expenditure and consumables usage (Marquez, 2007; Marquez and Cummings, 2008; Mackin et al., 2010). The next challenge will be to synchronize this information within the EVA timeline management functions demonstrated in Chapter 4 and 5.

### 7.2.3 Defining and Scoping Criteria for Future Operations

*Defining success criteria and influencing standards for future operations*

The high level design requirements defined in Chapter 3 offer an opportunity to begin the discussion surrounding acceptability criteria. How much error are we willing to live within an IV operators ability to synthesize timeline progress or recognize a subtle trend event? Establishing these standards will be a critical step in continuing this development effort as the EVA domain as a whole steps towards its future systems. The dependent variables established in Chapter 5 provide examples of measurable variables that could be useful for evaluating future EVA performance.

Additionally, NASA already utilizes a number of standards and processes documentation (e.g. NASA Standards 3001, Human Integration Design Processes) that could be revisited and refined based on the requirements derived in this thesis. Opportunities to refine these existing requirements to incorporate more detailed cognitive work and information relationship requirements may exist. These insights could play an important role in guiding systems design efforts by articulating what specific demands future systems should strive to support. As it stands right now, these existing standards are necessary but leave a gulf between what the desired end result is and how those specific objectives might be achieved. The requirements derived and demonstrated in this thesis are valuable in the process to bridge this gulf. Opportunities may also exist to more explicitly link elements of the Cognitive Work Analysis framework within these governing design processes as new techniques in better understanding system designs.

*Establishing a formal training program*

Training and 'best practices' will play an important role in this overall envisioning process. A concerted effort must be taken to account for the effects of learning and training effects as both scenarios and support system design mature. Fortunately, there exist numerous examples of incorporating and evaluating the impact of training practices into the experimental process, see Dahlstrom et al. (2009); Patterson et al. (2009); Fleming and Pritchett (2015) for a few useful exemplars.

*Extending Marvin to other components of EVA operations*

Marvin in its current form is designed specifically for the IV operator. However, opportunities exist to extend this platform to provide integrated support amongst the larger flight team. As a result, future iterations should aim to link both MCC, IV, and EV personnel under a suite of software tools that are linked to the underlying data demonstrated in this thesis. Care must be given to appropriately scoping the needs of each of these users so that support systems can be tailored to the user. Some preliminary work has already started investigating what support systems future EV crew might utilize within their spacesuits through the use of ‘heads-up’ displays and cuff-checklists (Simonds and Chen, 1991; Hodgson et al., 2003; Mackin et al., 2012; Sandor et al., 2012, 2013). However, MCC-centric support systems have not yet been addressed specifically for EVA. Furthermore, the integration of all these systems together as a collective flight team has not yet been examined. The hope here is that Marvin demonstrates a potential pathway to realizing systems that reference common critical data (e.g. timeline progress and life support system constraints) to enable the successful execution of future EVA operations.

# Appendices

# APPENDIX A

# DISSERTATION APPENDICES

## A.1 Word Domain Analysis - Interview and Abstraction Hierarchy Reference Materials

### A.1.1 Institutional Review Board - Interview Document

**School of Aerospace Engineering**
**Cognitive Engineering Center**
**Georgia Institute of Technology**
**Human Subject Consent**

1. **Project Title**: Decision Support System Development for Human Extravehicular Activity – Interview Phase

2. **Principal Investigator**: Dr. Karen Feigh, 404-385-7686, karen.feigh@gatech.edu
   **Graduate Students**: Matthew Miller, 912-674-6722, mmiller@gatech.edu
   **NASA JSC Mentor**: Dr. Kerry McGuire, 281-483-0786, kerry.m.mcguire@nasa.gov

3. **Protocol and Consent Title**: Decision Support System Development for Human Extravehicular Activity – Interview Phase

4. **Introduction**: The purpose of this study is to identify the current work practices of personnel who are employed in the domain of human extravehicular activities. You will be asked to participate in an interview which is tailored to explore your professional experiences with EVA missions.

5. **Procedures**:
   Introduction: The introductory briefing:
   - Seeks informed consent
   - Explains the interview format.

   Interview: You will be asked a series of questions concerning your employment the roles and responsibilities. We will then discuss in more detail your experiences interacting with and contributing to EVA mission(s). The format of the interview is semi-structured to allow for personalized answers and promote an environment for discussion. With your permission, we will audio record your responses, which will then be transcribed word-for-word for analysis. Your identity will not be revealed to anyone who hears the audio tape and only the identified persons will have access to the audio data. You may stop at any time and for any reason.

   The entire procedure will last approximately 1-2 hours. You are free to request a break at any time.

6. **Foreseeable Risks or Discomforts**: The probability and magnitude of harm or discomfort anticipated in the proposed research are not greater than those ordinarily encountered in everyday life or during performance of routine physical or psychological examinations or tests.

7. **Benefits**: There are no direct benefits to you for participating in this research study. The study will help lay the framework for future studies to enhance human EVA capabilities.

8. **Compensation/Costs**: There is no compensation for participation.

9. **Confidentiality**: Each participant will be randomly assigned a number, and their data will be recorded only in terms of that number. A key linking the number to each participant will be recorded in a password protected file on a password protected computer during data collection. Following data collection the file will be converted to hard copy and erased from the computer. The hard copy list will be kept behind a locked door in locked file cabinets in an office of the principal investigator, Dr. Karen Feigh (Guggenheim Room 425), and then destroyed once the study data analysis is complete. No information that could personally identify the participant will be asked of any participant. All electronic data (transcripts and reports) will be kept in password-protected files on password-protected computers. De-identified information resulting from the interviews will be collected in technical reports, conference papers, journal papers and academic dissertations and published. All data that are identifiable will be destroyed by secure erasure of digital copies or by shredding of paper- copies prior to the end of the study. The original voice recordings will be destroyed no later than three years after the last paper is published. To make sure that this research is being carried out in the proper way, the GT Office of Research Integrity Assurance and Johnson Space Center Institutional Review Board may review study records. The

APPROVED *Consent Form Approved by Georgia Tech IRB: April 22, 2014 - Indefinite*

Study ID:Pro1239 Date Approved: 5/12/2014 Expiration Date: 5/31/2015

Figure A.1: SME interview study consent form approved by Georgia Tech Institute and NASA Johnson Space Center Review Board - page 1.

Office of Human Research Protections may also look over study records during required reviews. The sponsor of this study, National Aeronautics and Space Administration (NASA), has the right to review study records as well.

**10. Injury/Adverse Reactions**: Reports of injury or reaction should be made to the Principal Investigator of this research study. Neither the Georgia Institute of Technology nor the principal investigator has made provision for payment of costs associated with any injury resulting from participation in this study.

**11. Contact Person**: If you have questions about the research, call or write Dr. Karen Feigh at 404-385-7686, Montgomery Knight Building, Room 419, Georgia Institute of Technology, 270 Ferst Drive, Atlanta GA 30332-0150.

**12. Voluntary Participation/Withdrawal**: You have the right to withdraw from the study at any time without penalty. The audio recordings along with all questionnaires and transcripts will be destroyed upon your withdrawal from the study.

**13. Participant's Rights:**

- Your participation in this study is voluntary. You do not have to be in this study if you don't want to be.
- You have the right to change your mind and leave the study at any time without giving any reason and without penalty.
- Any new information that may make you change your mind about being in this study will be given to you.
- You will be given a copy of this consent form to keep.
- You do not waive any of your legal rights by signing this consent form.

If you have any questions about your rights as a research volunteer, call or write:

Office of Research Compliance
Georgia Institute of Technology
Atlanta, GA 30332-0420
Voice (404) 894-6944 Fax (404) 385-2081

Your signature below indicates that the researchers have answered all of your questions to your satisfaction, and that you consent to volunteer for this study.

Subject's Signature: ______________________________________ Date: _______________

Subject's Name: ______________________________________

Investigator's Signature: ___________________________________ Date: _______________

Investigator's Name: ______________________________

APPROVED *Consent Form Approved by Georgia Tech IRB: April 22, 2014 - Indefinite*

Study ID:Pro1239 Date Approved: 5/12/2014 Expiration Date: 5/31/2015

Figure A.2: SME interview study consent form approved by Georgia Tech Institute and NASA Johnson Space Center Review Board - page 2.

### A.1.2 Exploratory Semi-Structured Interview Protocol

The following interview protocol was performed at the on-set of this research project to facilitate two purposes: 1) meet, interact with, and identify relevant EVA subject-matter experts and 2) supplement the EVA literature review that I was in the process of analyzing. These interviews in tandem with the literature review were directing the Work Domain Analysis model development efforts discussed in Section 3.2.1.

A semi-structured interview was selected to enable the opportunity to explore particular responses in more detail throughout the interview, rather than force the SME to respond to a predetermined set of questions. At this stage in the study, my focus was to acquire a sense of the challenges and organizational structure surrounding EVA operations, which aligns with my pragmatic worldview discussed in Section 2.5. In other words, these initial exploratory interviews provided evidence of methodology congruency with my worldview by providing a means to an end to support my initial information flow and abstraction hierarchy model development. These interviews alone did not wholly inform this WDA model develop process but rather helped orient myself to the domain under investigation.

The specific questions shown below were developed iteratively. First a broad set of questions were developed to address the following categories that I wanted to learn more about: Background, Roles & Responsibilities, Tasks in Nominal & Off-nominal situations, Information Flow, Decision making processes, Current Group Project capabilities and risks. I then performed a pilot interview session where I interviewed senior PhD candidates about a previous work experience as a surrogate for the EVA work domain. The intent here was to practice asking this initial question set and determine if the questions I asked were eliciting the information I desired. Furthermore, this pilot study allowed me to refine my question delivery and practice carrying the conversation for an extended period of time. After four separate one-on-one interviews, I reviewed my questions to examine if they did in fact yield the information I desired. Figure A.1 shows a summary of this process. Text highlighted in red signify changes that I made to refine the question and Y/N markers indicate whether the information discussed in the interview did or did not meet my expectations and whether they were feasible to ask during the conversation. Based on this refinement process, I down-selected the questions that had the most potential to elicit desired information from the SMEs within the target time frame of approximately a 90 minute interview session. Each SME interview was recorded and transcribed and coded in the similar open coding scheme I was developing based on my examination of the EVA literature review.

**Background**

- Could you briefly describe your involvement within the EVA community?

**Current EVA Ops**

- Could you please describe the latest EVA you were involved with?
  - What did you specifically contribute to the EVA?
  - Could you provide an explanation of your role(s) within this EVA?
  - Could you provide a description of your responsibilities?
  - Did these responsibilities change as the EVA progressed? If so, how?
- Could you discuss the decisions you made during nominal mission support operations to meet you responsibilities?
  - How did you make these decisions?
  - For this EVA, did you follow a specific set of guidelines or rules you to meet your responsibilities?
  - If so, could you describe them?
  - If not, how do you approach completing your responsibilities?
  - Follow-ups: how were your steps prioritized? does repetition steps occur? Are steps completed in parallel or sequential?
  - What information/resources did you have?
  - How do you use that information?
  - What would you have ideally liked to know?
  - What information/resources did you NOT need?
- Could you discuss the decisions you made during off-nominal mission support operations to meet you responsibilities?
  - How was the deviation diagnosed?

Table A.1: Exploratory semi-structured interview protocol development process.

| Category | Code | Question | Background -BA | Roles & Responsibilities -RR | Tasks – Nominal & Off-nominal -TA | Information Flow -IN | Decision making processes -DM | Current Group Project capabilities and risks -CR |
|---|---|---|---|---|---|---|---|---|
| Background | **1.0** | **Could you describe to me the path you have taken to get to your current position?** | X | | | | | |
| | 1.1 | How long have you been in your current professional role? | X | | | | | |
| | 1.2 | What educational training have you receive? (description and duration) | X | | | | | |
| | 1.3 | Have you been involved with group projects during your education? | X | | | | | |
| | 1.4 | What kinds of group projects have you had personal experience with? (classroom, research, work, etc?) | X | | | | | |
| | 1.5 | What is your typical work schedule like for a typical week? | X | X | | | | |
| | 1.6 | Who do you typically interact with? And why? (daily, weekly, monthly?) | X | X | | X | | |
| | 1.7 | What are your specific responsibilities in your current role as a graduate student? | X | | | | | |
| Specific EVA Mission | **2.0** | **Could you please describe the latest group project you were involved with?** | | | X | | | |
| | 2.1 | What specific class or research project was this project related to? | X | | | | | |
| | 2.2 | When the group project was scheduled, how do you learn about it? | | | | X | | |
| | 2.3 | Could you identify reasons for the group project to be scheduled? | | | X | | | X |
| | 2.4 | How did you and your group get acquainted with the new group project? | | | | X | | |
| | 2.5 | What was the overall group project timeline of events? | | X | | X | X | |
| | 2.6 | Who was in your group? | | | | X | | |
| | 2.7 | How did you communicate with during this project? | | | | X | X | |
| | 2.8 | What kind of information was exchanged? | | | | X | X | |
| | 2.9 | What was the purpose of the communication between the members? (e.g. provide instructions, monitor, etc.) | | | | X | X | |
| | 2.10 | Can you specifically describe how you and the rest of your group communicated? | | | | X | | |
| | 2.11 | How often did they communicate? | | | | X | | |
| | **3.0** | **What did you specifically contribute to the group project?** | | X | X | | | |
| | 3.1 | Could you provide an explanation of your role(s) within this group project? | | X | X | | | |
| | 3.2 | Could you provide an description of your responsibilities? | | X | X | | | |
| | 3.3 | Did these responsibilities change as the project progressed? If so, how? | | X | X | | | |
| | **4.0** | **Could you identify and describe the decisions you made to achieve your responsibilities?** | | X | | X | X | |
| | 4.1 | How did you make these decisions? | | | | X | X | |
| | 4.2 | For this group project, did you follow a specific set of guidelines or rules you to meet your responsibilities? | | | | X | X | |
| | 4.3 | If so, could you describe them? | | | | X | X | |
| | 4.4 | If not, how do you approach completing your responsibilities? | | | | X | X | |
| | 4.5 | Follow-ups: how are the steps prioritized? does repetition steps occur? Are steps completed in parallel or sequential? | | | | X | X | |
| | 4.6 | What information/resources did you have? | | | | X | X | |
| | 4.7 | How do you use that information? | | | | X | X | |
| | 4.8 | What would you have ideally liked to know? | | | | X | X | |
| | 4.9 | What information/resources did you NOT need? | | | | X | X | |
| | **5.0** | **Was there unplanned activity/events that occured during the project?** | | | X | | X | |
| | 5.1 | If so, could you please explain why this unplanned activity occurred? | | | X | | X | |
| | # | If not, could you describe another project that did not go as planned? | | | X | | X | |
| | 5.3 | What caused the deviation? | | | X | X | | |
| | 5.4 | How was the deviation diagnosed? | | | X | X | X | |
| | 5.5 | Who was involved in this process? | | | X | X | X | |
| | 5.6 | How was the deviation resolved? | | | X | X | X | |
| | 5.7 | Did this unplanned activity impact your work? | | | X | X | X | |
| | 5.8 | If so, how did it impact your work? | | X | X | X | X | |
| | 5.9 | How did this unplanned activity impact the group's goals? | | X | X | X | X | |
| | 5.10 | What were the risks associated with this unplanned activity? | | | | | | X |
| | **6.0** | **Where there any risks associated with in this group project? (e.g. schedule slip, health risks, not achieving project goals, etc)** | | | | | | X |
| | 6.1 | If so, how did you/the group go about minimizing this risk? | | | | | | X |

| Code | Interview #1: Was the question **asked directly**? | Was the question **addressed?** | Background -BA | Roles & Responsibilities -RR | Tasks – Nominal & Off-nominal -TA | Information Flow -IN | Decision making processes -DM | Current Group Project capabilities and risks -CR | Interview #2: Was the question **asked directly**? | Was the question **addressed?** | Background -BA | Roles & Responsibilities -RR | Tasks – Nominal & Off-nominal -TA | Information Flow -IN | Decision making processes -DM | Current Group Project capabilities and risks -CR |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.0 | Y | Y | Y | | | | | | Y | Y | Y | | | | | |
| 1.1 | N | Y | Y | | | | | | N | N | Y | | | | | |
| 1.2 | Y | Y | Y | | | | | | N | Y | Y | | | | | |
| 1.3 | N | N | | | | | | | N | Y | Y | | | | | |
| 1.4 | Y | Y | Y | | | | | | Y | Y | Y | | | | | |
| 1.5 | N | N | | | | | | | Y | Y | Y | N | | | | |
| 1.6 | N | N | | | | | | | Y | Y | Y | Y | | Y | | |
| 1.7 | N | N | | | | | | | Y | Y | Y | Y' | | | | |
| 2.0 | Y | Y | | | Y | | | | Y | Y | | Y' | N | | | |
| 2.1 | N | Y | Y | | | | | | | | | | | | | |
| 2.2 | N | Y | Y | | | | | | | | | | | | | |
| 2.3 | Y | Y | | | Y | Y' | | N | N | Y | Y' | Y' | Y | | | N |
| 2.4 | N | Y | | | | Y | | | N | N | | | | | | |
| 2.5 | Y | Y | | Y | | Y | Y | | Y | Y | | N | | N | N | Y' |
| 2.6 | Y | Y | Y' | | | N | | | N | Y | | | | Y | | |
| 2.7 | N | Y | | | | Y | Y | | Y | Y | | | | Y | Y | |
| 2.8 | N | N | | | | | | | N | N | | | | | | |
| 2.9 | N | N | | | | | | | N | Y | | | | Y | Y | |
| 2.10 | N | N | | | | | | | N | N | | | | | | |
| 2.11 | N | N | | | | | | | N | N | | | | | | |
| 3.0 | N | Y | | Y | Y | | Y' | | Y | Y | | Y | Y | | | |
| 3.1 | Y | Y | | Y | Y | | | | N | Y | | Y | Y | | | |
| 3.2 | Y | Y | | Y | Y | | | | N | Y | | Y | Y | | | |
| 3.3 | Y | Y | | Y | Y | | | | N | Y | | Y | Y | | | |
| 4.0 | Y | Y | | Y | | Y | Y | | N | Y | | | | Y | Y | |
| 4.1 | N | Y | | | | Y | Y | | N | Y | | | | Y | Y | |
| 4.2 | N | N | | | | | | | N | Y | | | | Y | Y | |
| 4.3 | N | N | | | | | | | N | N | | | | | | |
| 4.4 | N | N | | | | | | | N | N | | | | | | |
| 4.5 | N | N | | | | | | | N | Y | | | | Y | Y | |
| 4.6 | N | N | | | | | | | Y | Y | | | | Y | Y | |
| 4.7 | N | N | | | | | | | N | N | | | | | | |
| 4.8 | N | N | | | | | | | Y | Y | | | | Y | Y | |
| 4.9 | N | N | | | | | | | N | N | | | | | | |
| 5.0 | Y | Y | | | Y | | N | | Y | Y | | | N | | Y | |
| 5.1 | N | Y | | | Y | | N | | N | Y | | | N | | Y | |
| # | N | N | | | | | | | N | N | | | | | | |
| 5.3 | N | Y | | | Y | N | | | N | Y | | | N | Y | | |
| 5.4 | N | Y | | | Y | Y | Y | | N | N | | | | | | |
| 5.5 | N | Y | | | Y | Y | Y | | N | N | | | | | | |
| 5.6 | N | Y | | | Y | Y | Y | | Y | Y | | | | | | |
| 5.7 | N | Y | | | Y | Y | Y | | Y | Y | | | N | | Y | |
| 5.8 | N | Y | | Y | Y | Y | Y | | N | Y | | | N | | Y | |
| 5.9 | N | Y | | Y | Y | Y | Y | | N | N | | | | | | |
| 5.10 | N | N | | | | | | | N | N | | | | | | |
| 6.0 | Y | Y | | | | | | N | Y | Y | | | | | | Y |
| 6.1 | N | N | | | | | | | Y | Y | | | | | | Y |

| Code | Interview #3: Was the question **asked directly**? | Was the question **addressed?** | Background -BA | Roles & Responsibilities -RR | Tasks – Nominal & Off-nominal -TA | Information Flow -IN | Decision making processes -DM | Current Group Project capabilities and risks -CR | Interview #4: Was the question **asked directly**? | Was the question **addressed?** | Background -BA | Roles & Responsibilities -RR | Tasks – Nominal & Off-nominal -TA | Information Flow -IN | Decision making processes -DM | Current Group Project capabilities and risks -CR |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.0 | Y | Y | Y | | | | | | Y | Y | Y | | | | Y' | |
| 1.1 | N | Y | Y | | | | | | N | Y | Y | | | | | |
| 1.2 | N | Y | Y | | | | | | N | Y | Y | | | | | |
| 1.3 | N | N | | | | | | | N | N | | | | | | |
| 1.4 | N | N | | | | | | | N | N | | | | | | |
| 1.5 | Y | Y | Y | N | | | | | Y | Y | Y | Y | Y' | | Y' | |
| 1.6 | Y | Y | Y | N | | N | | | N | N | | | | | | |
| 1.7 | N | N | | | | | | | N | N | | | | | | |
| 2.0 | Y | Y | Y' | | Y | | | | N | Y | Y' | | Y | | | |
| 2.1 | N | Y | Y' | | | | | | Y | Y | Y' | | | | | |
| 2.2 | N | N | | | | | | | N | Y | | | | | | |
| 2.3 | N | Y | Y' | | N | | | N | N | N | | | | | | |
| 2.4 | N | N | | | | | | | N | N | | | | | | |
| 2.5 | N | N | | | | | | | Y | Y | | N | | N | Y | |
| 2.6 | N | Y | | Y' | | N | | | N | Y | | | | N | | |
| 2.7 | N | Y | | | | Y | N | | Y | Y | | Y' | | Y | Y | |
| 2.8 | N | N | | | | | | | Y | Y | | | | Y | Y | |
| 2.9 | N | Y | | | | Y | N | Y' | N | Y | | | | Y | Y | |
| 2.10 | Y | Y | | | | Y | | | Y | Y | | Y' | | Y | | |
| 2.11 | Y | Y | | | | Y | | | Y | Y | | Y' | | Y | | |
| 3.0 | Y | Y | | Y | Y | | | Y' | Y | Y | | Y | Y | | | |
| 3.1 | Y | Y | | Y | Y | | | | Y | Y | | Y | Y | | | |
| 3.2 | Y | Y | | Y | Y | | | | Y | Y | | Y | Y | | | |
| 3.3 | N | N | | | | | | | N | | | | | | | |
| 4.0 | Y | Y | | Y | | Y | Y | Y' | Y | Y | | Y | Y' | Y | Y | |
| 4.1 | N | Y | | | | Y | Y | | N | N | | | | | | |
| 4.2 | N | N | | | | | | | N | N | | | | | | |
| 4.3 | N | N | | | | | | | N | N | | | | | | |
| 4.4 | N | Y | | | | Y | Y | | N | N | | | | | | |
| 4.5 | N | Y | | | | Y | Y | | N | N | | | | | | |
| 4.6 | Y | Y | | | | Y | Y | | Y | Y | | | | Y | Y | |
| 4.7 | N | Y | | | | Y | Y | | Y | Y | | Y' | | Y | Y | |
| 4.8 | N | Y | | | | Y | Y | | Y | Y | | | | Y | Y | |
| 4.9 | Y | Y | | | | Y | Y | | Y | Y | | | | N | N | |
| 5.0 | Y | Y | | | Y | | Y | Y' | Y | Y | | | Y | Y' | Y | |
| 5.1 | Y | Y | | | Y | Y | | | N | Y | | | Y | Y' | Y | |
| # | N | N | | | | | | | N | N | | | | | | |
| 5.3 | N | Y | | | Y | Y | | | N | Y | | | Y | Y | | |
| 5.4 | N | N | | | | | | | N | N | | | | | | |
| 5.5 | N | N | | | | | | | N | Y | | | Y | Y | Y | |
| 5.6 | Y | Y | | | Y | Y | Y | | N | Y | | | Y | Y | Y | |
| 5.7 | N | N | | | | | | | Y | Y | | | Y | Y | Y | |
| 5.8 | N | N | | | | | | | N | N | | | | | | |
| 5.9 | N | N | | | | | | | N | N | | | | | | |
| 5.10 | N | N | | | | | | | N | N | | | | | | |
| 6.0 | Y | Y | | | | | | Y | Y | Y | | | | | | Y |
| 6.1 | Y | Y | | | | | Y' | Y | Y | Y | | | | | | Y |

- How was the deviation resolved?
- How did you make these decisions?
- For this EVA, did you follow a specific set of guidelines or rules you to meet your responsibilities?
- If so, could you describe them?
- If not, how do you approach completing your responsibilities?
- Follow-ups: how were your steps prioritized? does repetition steps occur? Are steps completed in parallel or sequential?
- What information/resources did you have?
- How do you use that information?
- What would you have ideally liked to know?
- What information/resources did you NOT need?

**Future EVA Ops**

As NASA moves towards more ambitious deep-space missions, EVA astronauts will not have the same time-delay communications with mission control as they currently do in low Earth orbit. Missions to Mars have communication time-delays on the order of 4 to 20 minutes. This set of questions is about exploring future EVA missions where astronauts will conduct EVAs in communication delayed environments like deep-space.

- What challenges to you believe Astronauts and Flight Controllers face in operating in a time-delayed support environment?
- What aspects of the current operations of EVAs do you believe will need to be altered to achieve EVA mission success?
- What risks do you believe exists in changing these operations?

**Wrap-Up**

- Can you think of anything else that could help me in my research efforts? (e.g. additional people to talk with?)
- Do you have any questions for me?

#### A.1.3 Institutional Review Board - Interview and Observation Document

**School of Aerospace Engineering**
**Cognitive Engineering Center**
**Georgia Institute of Technology**
**Human Subject Consent**

1. **Project Title**: Decision Support System Development for Human Extravehicular Activity

2. **Principal Investigator**: Dr. Karen Feigh, 404-385-7686, karen.feigh@gatech.edu
   **Graduate Students**: Matthew Miller, 912-674-6722, mmiller@gatech.edu
   **NASA JSC Mentor**: Dr. Kerry McGuire, 281-483-0786, kerry.m.mcguire@nasa.gov

3. **Protocol and Consent Title**: Decision Support System Development for Human Extravehicular Activity

4. **Introduction**: The purpose of this study is to understand the current work practices and support activities of flight controllers who support NASA human extravehicular activity. We are seeking your permission to observe you as your perform your flight controller duties. You will be asked to participate in an observational study, with possible follow-up interviews and surveys to understand your work practices as an EVA flight controller.

5. **Procedures**:
   Introduction: The introductory briefing:
   - Seek informed consent
   - Explain the study format

   Participation: This study will consist of the study personnel being co-located with you, the study participant, so that the study personnel can witness first-hand your work as you perform it. For the most part, the observations will be made without disturbing or disrupting the study participant. Potential follow-up discussions after the observation session with participants will supplement observations with additional information about how your work contributes to the overall EVA. Additionally, recorded voice loop data may be used to supplement the observations. Your identity will not be revealed to anyone and only the identified persons will have access to the data. You may stop at any time and for any reason.

   The observation portion of this study will last a minimum of 1 hour up to approximately the duration of your work shift. Potential follow-up discussions which could include interviews and surveys will last approximately 1-2 hours and will be scheduled at your convenience. You are free to request a break at any time and you have the right to withdraw from this study at any time.

6. **Foreseeable Risks or Discomforts**: The probability and magnitude of harm or discomfort anticipated in the proposed research are not greater than those ordinarily encountered in everyday life or during performance of routine physical or psychological examinations or tests.

7. **Benefits**: There are no direct benefits to you for participating in this research study. The study will help lay the framework for future studies to enhance human EVA capabilities.

8. **Compensation/Costs**: There is no compensation for participation.

9. **Confidentiality**: Each participant will be randomly assigned a number, and their data will be recorded only in terms of that number. A key linking the number to each participant will be recorded in a password protected file on a password protected computer during data collection. Following data collection the file will be converted to hard copy and erased from the computer. The hard copy list will be kept behind a locked door in locked file cabinets in an office of the principal investigator, Dr. Karen Feigh (Guggenheim Room 425), and then destroyed once the study data analysis is complete. No information that could personally identify the participant will be asked of any participant. All electronic data (notes and reports) will be kept in password-protected files on password-protected computers. De-identified information resulting from the observations will be collected in

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Study ID:Pro1239 Date Approved: 5/12/2014 Expiration Date: 5/31/2015

Figure A.3: SME interview/Observation study consent form approved by Georgia Tech Institute and NASA Johnson Space Center Review Board - page 1.

technical reports, conference papers, journal papers and academic dissertations and published. All data that are identifiable will be destroyed by secure erasure of digital copies or by shredding of paper- copies prior to the end of the study. To make sure that this research is being carried out in the proper way, the GT Office of Research Integrity Assurance and Johnson Space Center Institutional Review Board may review study records. The Office of Human Research Protections may also look over study records during required reviews. The sponsor of this study, National Aeronautics and Space Administration (NASA), has the right to review study records as well.

10. **Injury/Adverse Reactions**: Reports of injury or reaction should be made to the Principal Investigator of this research study. Neither the Georgia Institute of Technology nor the principal investigator has made provision for payment of costs associated with any injury resulting from participation in this study.

11. **Contact Person**: If you have questions about the research, call or write Dr. Karen Feigh at 404-385-7686, Montgomery Knight Building, Room 419, Georgia Institute of Technology, 270 Ferst Drive, Atlanta GA 30332-0150.

12. **Voluntary Participation/Withdrawal**: You have the right to withdraw from the study at any time without penalty. The audio recordings along with all questionnaires and transcripts will be destroyed upon your withdrawal from the study.

13. **Participant's Rights:**
    - Your participation in this study is voluntary. You do not have to be in this study if you don't want to be.
    - You have the right to change your mind and leave the study at any time without giving any reason and without penalty.
    - Any new information that may make you change your mind about being in this study will be given to you.
    - You will be given a copy of this consent form to keep.
    - You do not waive any of your legal rights by signing this consent form.

If you have any questions about your rights as a research volunteer, call or write:

Office of Research Compliance
Georgia Institute of Technology
Atlanta, GA 30332-0420
Voice (404) 894-6944 Fax (404) 385-2081

Your signature below indicates that the researchers have answered all of your questions to your satisfaction, and that you consent to volunteer for this study.

Subject's Signature: ______________________________ Date: ____________

Subject's Name: ______________________________

Investigator's Signature: ____________________________ Date: ____________

Investigator's Name: ________________________

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Figure A.4: SME interview/Observation study consent form approved by Georgia Tech Institute and NASA Johnson Space Center Review Board - page 2.

### A.1.4 WDA Interview Resource Material

The work of Naikar et al. (2005) provided the following interview question material to facilitate the AH model construction process. Below summarizes the model review process and material utilized to facilitate the interviews. A key component of this process was that I first generated preliminary models based on a thorough examination of relevant EVA work domain documentation at which point, SME input was obtained to refine and finalize the model content.

- The interviewee, who was an EVA SME, was provided a brief recap of model development process I had performed to-date, which consisted of informing the SMEs the various documents I have studied, observational session conducted and the overall motivation for this work.
- The SME was then provided an overview of the structure of the content to be discussed regarding the abstraction hierarchies. I presented a brief description of what each level entailed as described below.
- Once the SME felt comfortable with the aims of the interview, we reviewed the structure of AH models by reviewing each of the levels, the content they contained.
- The SME was then asked to review each AH element within each level of the models. Once reviewed, we engaged in dialog regarding whether the information was comprehensive in depicting the level, as well as critiqued the stated content for accuracy and consistency. One key focus here was to ensure the stated AH model elements were clear to the SME.

**Functional Purpose Level**

- For what reasons does the work system exist?
- What services does the work system provide to the environment?
- What has the work system been designed to achieve? (Think: reasons, goals, objectives, aims, intentions)
- What kinds of constraints does the environment impose on the work system?
- What laws and regulations does the environment impose on the work system?

**Abstract Purpose Level**

- What criteria can be used to judge whether the work system is achieving its purposes?

- What criteria can be used to judge whether the work system is satisfying its external constraints?
- What are the priorities of the work system? (Think: Measures of: effectiveness, efficiency, reliability, risk, resources, success)

**Generalized Purpose Level**

- What functions are required to achieve the purposes of the work system?
- What functions are required to satisfy the external constraints on the work system?
- What functions are performed in the work system? (individuals, teams, and departments) (Think: roles, responsibilities, purposes, tasks, activities operations)

**Physical Function Level**

- What can the physical objects in the work system do or afford?
- What are the functional capabilities and limitations of physical objectives in the work system?
- What functionality is required in the work system? (Think: processes, functions, capabilities, physical processes, mechanical processes)

**Physical Form Level**

- What are the physical objects or physical resources in the work system both natural and man-made?
- What physical objects or physical resources are necessary to enable to the processes and functions of the work system?
- What are the material characteristics and the organization of physical objects/resources in the work system? (Think: tools, equipment, resources, material characteristics, topography)

The WDA data analysis was performed using a combination of software tools. First the data was coalesced and examined in Atlas.ti7[1]. Once the model development process began to be reviewed by SMEs, other tools such as Microsoft Visio and Office tools were used to represent and manage the model content. Figure A.5 shows an excerpt from the early model development process in Atlas.ti where semi-structured interview transcripts and EVA literature were coded with categories to facilitate the model construction process.

[1]For more information on this qualitative software, see http://atlasti.com/

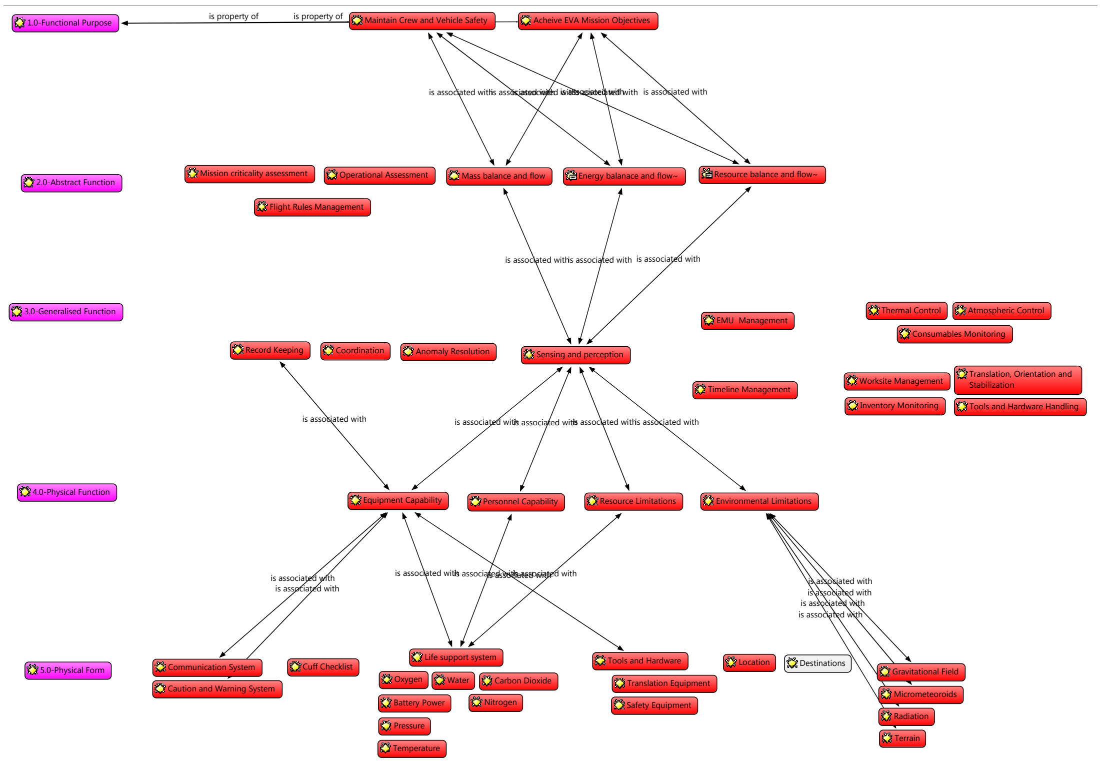


Figure A.5: Excerpt of the Abstraction Hierarchy model development process using Atlas.ti7.

## A.2 Control Task Analysis - Decision Ladder Model Results

### A.2.1 Content and Structure

This section shows the full list of requirements as derived from the process describe in Chapter 3. The general interview process to construct and review the decisions ladders is described below:

- The interviewee, who was an EVA SME, was provided a brief recap of model development process I had performed to-date, which consisted of informing the SMEs the various documents I have studied, observational session conducted and the overall motivation for this work.
- The SME was then provided an overview of the structure of the content to be discussed regarding the decision ladders. I presented the decision ladder model as shown in Chapter 3. I then stepped through each of the stages described in Table A.2 to describe the type of information and content that I was seeking for model development and refinement.

- Once the SME felt comfortable with the aims of the interview, we reviewed the structure of requirements matrix by reviewing each of the columns, the content they contained, and how we would approach each section.
- The SME was then asked to review each SoK, CWR, and IRR pairing within each stage of the decision ladder. Once reviewed, we engaged in dialog regarding whether the information was comprehensive in depicting the stage, as well as critiqued the stated content for accuracy and consistency. One key focus here was to ensure the stated requirements were clear to the SME.
- As the facilitator of this interview, I recorded notes along side each requirement as the SME and I discussed each line item. This information was then used to generate the overall intent descriptions provided alongside each requirement pair.

The remainder of this section provides the full list of requirements, arranged by decision ladder stage. At the beginning of each decision ladder, a summary of which requirements are located with which stage of the decision is provided.

#### A.2.2 Life Support System (LSS) Management Results

Tables A.3 through A.12 provide the full list of life support system management requirements. Figure A.6 provides a summary view of which requirements are associated with each stage of the decision ladder.

#### A.2.3 Timeline Tracking and Alteration (TTA) Results

Tables A.13 through A.23 provide the full list of timeline tracking and alteration requirements. Figure A.7 provides a summary view of which requirements are associated with each stage of the decision ladder.

# Table A.2: Decision ladder stage descriptions

| | | Bisantz and Burns (2009) (pg. 104) | | Naikar (2006), Table 4 | |
|---|---|---|---|---|---|
| **DL Stage** | **Vicente (1999)** | **Bos et al. (2005)** | **Sartori et al. (2006)** | ***Description*** | ***Keywords*** |
| **Activation** | Detections of need for actions | Perception | All possible ways that an operator can be alterted to the need for an activity | What kinds of events can act as alerts? | see, hear, notice, detect, signal, alarm, warning |
| **Alert** | What is going on? | Realization | All possible examples of what it "looks like" when someone has noticed the need to act | | |
| **Observe** | Information and data | Display of contacts and other informaiton | All possible processes through which observations are collected | What kinds of data or facts are available? | Watch, monitor, look out for, search, gather, check, examine, inspect, data, facts, information |
| **Set of Observaitons** | What lies behind? | A corpus of information | Collectively, all the information known about a single contact | | |
| **Identify** | Present state of the system | Consider the information | All possible inferences based on known information | | |
| **System State** | What is the effect? | What does this mean? | Into which standard ID category does this contact fit, how detailed is my recognitition assessment? | What kinds of asssessments about the system's condition or situation are possible with the information? | Recognize, establish, determine, infer, diagnose, interpret, estimate, calculate, figure out, condition, situation circumstances, status |
| **Interpret** | Consequences for current task, safet, efficiency, etc. | How does this fit in my "idealized" progress toward my goal? | All possible implications of the contact on our mission | | |
| **Ambiguity (Options)** | Which goal to choose? | I do not know how this fits | All possible reasons why we might still be unsure what this means for the mission. Where is the uncertainty? | What kinds of choices or alternatives are available for the system's desired or target state? | Choose, select, consider, pick, assess, appraise, judge, evaluate, decide, options, choices, alternatives |
| **Evaluate Performance Criteria** | - | How does it need to fit? | All possible to interpret this data, so we can get a probabilistic idea of what it means | | |
| **Ultimate Goal** | Which is then the goal state? | This has this effect on my ultimate goal | All possible ways this ambiguous informaiton can change my goal? How? | What kinds of aims or objectives can be relevant or influence decisions? | Achieve, fulfil, satisfy, accomplish, goals, aims, objectives |
| **Interpret** | Consequences for current task, safety, efficiency, etc. | What steps do I need to add to get my progress back on track? | All possible outcomes in progress towards accomplishing goals | | |
| **Goal State (Target State)** | Which is the appropriate change in operating conditions? | Know what you want to achieve | All possible ways that subgoals may be modified/added/removed to accomplish the ulitmate goal | What kinds of target states are possible? | Same as for options or references to what to do about the current situation or what changes to make to the current situation |
| **Define Task** | Select appropriate change of system conditions | Determine what you need to do | What possible ways can I cachieve my new goals from my current starting point? | What kinds of tasks are necessary and what kinds of resources are available? | Plan, designate, allocate, identify, tasks, resources |
| **Task** | How to do it? | Know what you need to do | Collective list of the tasks identified in the Define Task step | What kinds of procedures or sequences of steps are necessary? | Schedule, specify, formulate perform, carry out, conduct, procedures, processes, **timings,** instructions, tasks, actions |
| **Formulate Procedure** | Plan seqences of actions | Plan how to do it | Determine the specific actions involved in accomplishing tasks | | |
| **Procedure** | - | Know how to do it | Knowing what to do | | |
| **Execute** | Coordinate manipulations | Do it | Do it | - | - |

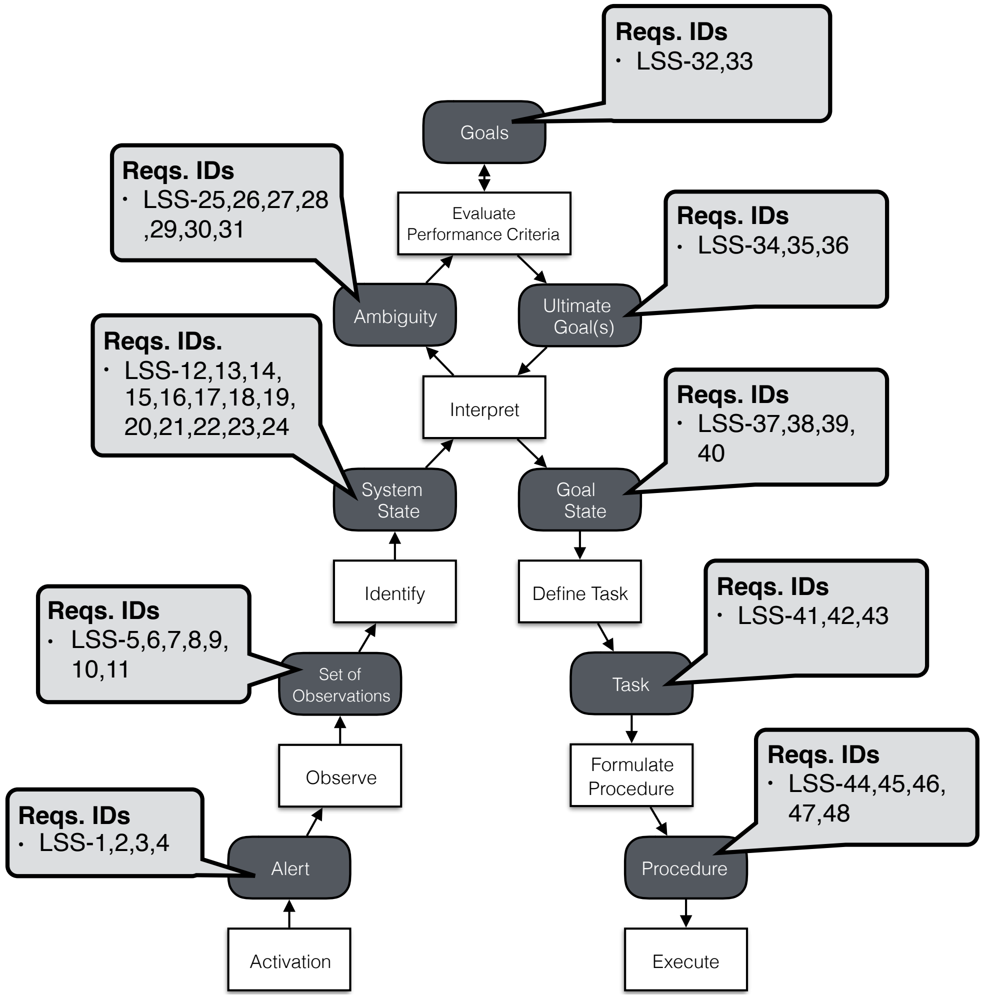


Figure A.6: Decision ladder summary of results for life support system (LSS) management

Table A.3: Decision ladder results for LSS - Alert stage

## LSS - Alert State

| ID | SME State of Knowledge (SoK) | Cognitive Work Requirements (CWR) | Information Relationship Requirement (IRR) | Requirement Intent |
|---|---|---|---|---|
| LSS - 1 | Are the data values within expected bounds? | The DSS Shall assess the real-time life support data values in comparison to expected data values | Calculate deviation/ difference in real-time data w.r.t. expected values over time [current data - expected data value per unit time] | The extravehicular mobility unit (EMU) can be considered in two components: the spacesuit assembly which consists of the soft goods (the pressure vessel) and the life support system (LSS). Biomedical data is outside the scope of this study. Currently, the synthesis process of the LSS consists of limited computer support and is manually performed by flight controllers. Outside of a limited subset of critical engineering limits, LSS variables are monitored and compared real-time to operator's internal knowledge of what are considered appropriate values and trends. Additionally, LSS variables are usually cross-correlated with other variables. |
| LSS - 2 | How are data values trending in time? | The DSS shall assess real-time life support data in comparison to expect transient data value behavior | Calculate temporal trends 'within acceptable boundary limits' between actual and expected trends | Data trending is an important forecasting and diagnosis tool for LSS understanding. Not only do trends provide insight into system understanding, but they provide secondary indicators as to how the crew are performing. Currently, real-time execution involves associating instantaneous and aggregate averaged values (e.g. O2 use rate over tha past 10 data passes and overall avg O2 use rate). There is a huge potential here for drawing upon historical records to `overlay` past trends with current trends for comparison. The span of time over which variables are monitored and assessed is also important. For instance, metabolic rate is monitored instantaneously as well as averaged over the past 10 data passes to provide two different perspectives of the same variable. The time scale over which a data value is monitored is an important facet of data monitoring. This concept of time windows will be an important component of trending analysis. Trending data provides a way of anticipating potential future problems. When assessing variables, questions such as: "Is variable acceptable for now but trending in the wrong direction? How long do you potentially have to get to that violation point in the trend?" Additionally, data trends are not just considered on a per variable basis, but rather data trends are examined among a collective set of observations. Therefore, knowing how each data trend evolves relative to other correlated data variables is an important feature of alerting. |
| LSS - 3 | Are system configurations in desired/undesired modes? | The DSS shall track the state and changes of state in comparison to expected configuration(s) | Track/calculate values and deviation of mode values and mode changes between actual and expected | Modes of operations will likely only increase as the LSS transitions to a more digital (software driven) configuration. Knowing what state a particular system or subsystem exists in is paramount to having accurate expectations of what the system should (could) be doing. We can potentially leverage the modes of operations of the airline operations industry for guidance here. There exist dynamic and static phases of operations and transitions that must occur during EVA execution, therefore the transitions between these phases will become important. You know what you are doing and where you are, but does the suit also know so it can meet the demands and expectations of the task and environment? Currently, crew can accidentally bump a switch on their display control unit (DCU) and knock a subsystem out of the desired mode, so even something as simple as an unintended mode change needs to be captured and resolved. |
| LSS - 4 | What are the contents of crew calls of environmental/ system changes? | The DSS shall incorporate operator information to related described content with known system content | Compare key content vocabulary/syntax with system database knowledge | Crew are a vital sensor within the spacesuit. What crew say to describe their situation is valuable data so it therefore makes sense to incorporate that data type/format somehow into the DSS in a meaningful way. Incorporating crew input would allow enable data acquisition that does not necessarily have a sensor or perhaps the data is missing from the telemetry stream. You can also potentially obtain crew distress or fatigue insight based on their audio communication. Cuff checklists provide a condensed list of words to describe situations that could be used as a starting point for crew/system training. We'll obviously need to have both the crew and system speaking the same natural language for any of this to work. Additionally, audio is the natural form of communication and interaction during EVA, so we should keep that in mind when we start to propose actions or technologies that are not audio-focused. |

Table A.4: Decision ladder results for LSS - Sets of Observations stage

## LSS - Set of Observations

| ID | SME State of Knowledge (SoK) | Cognitive Work Requirements (CWR) | Information Relationship Requirement (IRR) | Requirement Intent |
|---|---|---|---|---|
| LSS - 5 | What are my current console data values and how do they present in relation to the altered variable(s)? | The DDS shall assess real-time life support data in comparison with expected correlations between variables | Calculate temporal and discrete trends between life support system variables and compare those relations to expected relations | A single data value rarely presents itself in isolation as being anomalous. Therefore, we need to be able to aggregate additional variables related to specific sets of variables of interest to generate a list of correlated data behavior. As a simple example, the crew convey an increase in temperature, the flight controllers could inspect both the fan speed variable and associated amperage draw to check on subsystem functionality. Sets of observations include not only trend data but instantaneous failures (discrete values). Additionally, each suit/crew member combination will have unique performance characteristics to take into account. Historical regressions and probability distributions will grow and become a part of the diagnosis process to help support operations on a per suit/hardware basis. Two additional perspectives exists: “Out of family” data points can exist with regard to how a suit typically behaves with a particular crew member; and how that suit/crew combination performs with regards to engineering specifications. Currently, flight controllers manually manage this insight to apply during execution. |
| LSS - 6 | What are my most accurate/reliable sources of data? | The DSS shall assess the validity of sensor data being recorded | Calculate the likelihod of false positives or confidence level in the asessment of sensor readings | Accuracy can be viewed in two ways. 1) accuracy at the local sensor level and 2) accuracy at the systems level. Sensors have physics-based resolutions that should already be quantified explicitly and factored into the readings. But with a set of observations, accuracy among various sensors then takes on a meaning of confirming cues. The identification of conflicts between sensor data and crew input can provide a more operational view of accuracy. Cues can be used to confirm or deny the existence of a situation, leading to subsequent actions. Both forms of accuracy are important to capture in a DSS. (Pritchett, 2009) provides a great account of the sensor level issues associated with sensors and alerting. Numerous publications can be referenced to think about cue utilization in operations (Janssen, Brumby, & Garnett, 2012; Loveday, Wiggins, & Searle, 2013; Ngo, Pierce, & Spence, 2012). Finally, there is an ordering of severity or relative importance that must be accounted for in the set of observations. Not all variables carry the same weight or level of importance for a particular situation. Flight controllers rely on pattern matching with institutional knowledge and experience to guide their prioritization efforts to “know where to look” to gather these observations. |
| LSS - 7 | What are the potential fault tree paths given the current console values? | The DSS shall generate and enable the exploration of fault tree paths for diagnosis support of LSS | Generate potential fault tree paths by associating sensor readings with related system hardware knowledge and flight rule specifications (Fault Tree Analysis capabilities) | Operational fault trees are a specific tool to aid in the troubleshooting process**.** This is a tool used to identify and resolve unexpected situations. The intent of operational fault trees is not to necessarily capture the underlying engineering related source of the issue, but rather to acquire what operational actions must now be taken. Fault trees can be a quick way of resolving a potential issue or generating a course of action. Knowing what the implications of the situation can also dictate the resulting action(s), particularly when crew safety is at risk. But the first order of business is generating the relevant tree branches to include for investigation (if it is needed at all). More traditional engineering fault trees are generally left for post-EVA analysis for a full system diagnosis. During execution, generating exhaustive fault trees may not yield useful insight in the time available to guide crew actions. Are there confirming/denying cues? Not just temporal trends and correlation trends. |
| LSS - 8 | What are the current mechanical configurations of the system? | The DSS shall assess the discrete states of the LSS and any other interfaces that may interact or influence the LSS | Calculate and compare mode states of LSS to desired configurations | The LSS operates under discrete modes of operation (at a system level as well as at a subsystem level). Awareness of and the appropriateness of those states must be captured. In terms of operability, there is also the need to not only ensure desired LSS states but also be aware of interfaces with external systems and the status of those systems. Both the LSS and the external system must be in the correct configurations to secure a desired interface. (See (Abercromby, Chappell, & Gernhardt, 2013) for future potential interface configurations) |
| LSS - 9 | What are the current environmental conditions? | The DSS shall assess the external environmental states | Calculate and compare environmental conditions in relation to LSS states | Environmental conditions are paramount to making sure the crew are operating with “safe” environmental parameters. This requirement arose from the discussion and evaluation of the other “states of observation.” Variables such as lighting conditions, thermal, EM, hardware-related are all important to synthesize to understand their implications on LSS performance. |
| LSS - 10 | What is the crew telling me about the state of the system? (spacesuit and self-diagnosis) | The DSS shall incorporate operator information to related described content with known system content | Compare crew input with system data to establish confidence in system undertanding (support fault tree analysis) | The crew are a vital source of information regarding LSS performance. Therefore, we logically conclude that the ability to synthesize crew input is paramount to gathering a complete set of observations for EVA understanding. LSS-10 requirements emphasizes that system understanding will leverage a variety of sources, many of which have no direct insight or sensors to leverage. Historical data provides an additional level of insight into LSS performance. Additionally, this variety of data sources can be used as confirming or denying cues to agree/disagree with actual sensor data and support fault tree analyses. |
| LSS - 11 | Where are the crew in the timeline? (associate console values with tasks performed) | The DSS shall estimate the location in time and space of the EV crew members within the planned timeline | Associate the performed and current LSS demands with planned/expected performance from the planned timeline | The timeline assumes the life support system can support those specific actions. Elements to consider here include: ``Is what the crew are doing causing the LSS state changes? If so, are we happy with these changes in the moment?" These requirements convey the importance of associating LSS data observations with as-performed tasks to know if the data presented is reasonable and acceptable. (e.g. Does the metabolic rate seem higher than it should be, given the specific actions of the crewmember?) |

Table A.5: Decision ladder results for LSS - System State stage

## LSS - System State

| ID | SME State of Knowledge (SoK) | Cognitive Work Requirements (CWR) | Information Relationship Requirement (IRR) | Requirement Intent |
|---|---|---|---|---|
| LSS - 12 | Do conflicting data sources exist? | The DSS shall discriminate between conflicting LSS data sources | Compare current data values with known accepted values/ behaviors at the subsystem level | A multitude of data sensors can present with conflicting data values. Therefore, we must identify what possible conflicting data sources do exist. As a result of our discussions, the concept of prioritizing data values is an important component of this system state process. How severe a set of data present themselves will guide the subsequent actions. Additionally, analog, digital, and other forms of data such as audio information will likely need to be integrated as a complete suite to meet this requirement. |
| LSS - 13 | What are the confirming cues for fault tree analysis? | The DSS shall navigate fault tree branches to support fault tree analysis and problem diagnosis | Calculate and relate the subsystem and sensor data and crew input to compare current states with known accepted values | The identification of confirming cues is an important part of that LSS understanding. This will require not only comparing sensor data to the situation (or hypothesized situation) but it will need to incorporate crew audio input as part of this process. The aggregated set of data together provide insight into then building and navigating the potential fault trees applicable to the given situation. |
| LSS - 14 | Is there missing data in the set of observations that needed to perform hypothesis testing for assessing system functionality? | The DSS shall track data omissions in LSS assessments | Track data values that are and are not included in LSS assessments | Even if all available data is gathered, there might still be missing data that may be of use. Therefore, it is important to capture and track the availability of data as well as relate the information to the hypothesis generating and testing process. You can only make an informed understanding of system state if you have all relevant data available or accessible. Knowing the implications of what is lost in terms of data sensors is also an important component of gaining state understanding. Flight controllers are currently expected to make informed decisions without necessarily a full data set, therefore future systems must consider this operational reality. |
| LSS - 15 | How much time do I have/ need to understand the problem/situation? | The DSS shall assess the urgency associated to LSS anomalies | Calculate urgency criteria based on *a priori* set criteria and real-time contextual features | The "Time to Effect" phenomenon is a vital component of system understanding to support EVA execution. In general, this term refers to the generation of solutions that can have meaningful impact within an appropriate amount of time. This is tightly coupled with this notion of priority [severity] stated earlier. Flight controllers tend to assume the worst case until they can prove otherwise and use agreed upon pathways to ingress when faced with high severity situations. The urgency of the situation is simultaneously accounted for while acquiring system state understanding using these pathways. |
| LSS - 16 | What is the current mental/physical state of the crew? | The DSS shall assess crew physiologic and mental state | Compare physiological and auditory data to historical records to estimate crew mental/ physical status | This requirement is coupled with Flight Surgeon. Currently, crew are responsible for tracking their own physical and mental fatigue. In general, this is process is meant to be an open dialog amongst the team to make realistic predictions/extensions of the EVA based on crew capability. This requirement relates physiological data to historical patterns for analysis as a means to understand how that crew member is performing now in relation to their past performances. This insight, coupled with real-time crew input, provides a more complete physiological picture. |
| LSS - 17 | What is the state of the spacesuit? (degrees of safe functionality) | The DSS shall track the degrees of functionality of LSS subsystems | Track/Calculate the functionality of LSS subsystems by assessing current data with known accepted values | There exist engineering limits (e.g. how the spacesuit was designed to performed) and operational limits (e.g. limits we allow the spacesuit to be operated within). Both are vital to consider during execution. This requirement aims to synthesize this vast array of data on a per suit per crewmember basis to generate a living history of data so that anomalies from historical record can be more easily identified. This is particularly important with respect to catching issues before they become issues, or when considering to restructure timeline elements and if the spacesuit can support those alterations. This requirement could be coupled with the suit Caution and Warning System (CWS) as a means to having a robust system state understanding. |
| LSS - 18 | What are the applicable flight rules relevant to the current state of the spacesuit/crew? | The DSS shall incorporate applicable flight rules with real-time operational context | Calculate zones of acceptable operation by comparing EVA operational context from sensor/ timeline data with *a priori* specified flight rules | Flight rules help describe the rules within which the astronauts must operate. They are safety oriented in order to maintain safe conditions for operations. Flight rules can have black and white descriptions but there is often an ambiguous area of operations which require interpretation and application of flights rules to the current situation. This requirement states that flight rules must be ingested into the system in a way that synchronizes crew state information with applicable flight rules. Furthermore, the system should be able to provide the crew with a sense of where the crew are in the gray areas of the rules. Crews will ultimately need to make decisions for themselves, and providing them with the flight rules in context is important to ensuring safe operations. |

Table A.6: Decision ladder results for LSS - System State stage (continued)

## LSS - System State Continued

| ID | SME State of Knowledge (SoK) | Cognitive Work Requirements (CWR) | Information Relationship Requirement (IRR) | Requirement Intent |
|---|---|---|---|---|
| LSS - 19 | How much redundancy for critical systems is available? | The DSS shall track the redundancy of the LSS | Associate LSS state status with known tolerances of system redundancies | Awareness of system redundancies is important when making operational decisions. Having a system that is aware of how close redundant systems are to the brink of operation provides an additional layer of insight to make redundancy assessments (Requirements: LSS 17 and 19 contribute towards LSS 15 to make that assessment) |
| LSS - 20 | What tasks have been performed and how has the LSS performed during those tasks? | The DSS shall track timeline task progress in relation to current (and historical) life support system performance | Compare the current state of life support system variables to expected telemetry profiles, given timeline progress | The evolution of LSS state variables is unique for each and every EVA. As tasks are completed, the LSS varies in its ability and capacity to support life. Therefore, it is important to be able to associate task execution with LSS performance throughout the EVA. This requirement aims to emphasize the real-time synthesis capability of archiving and processing data during execution to build a living history of performance during the EVA. |
| LSS - 21 | Is task(procedure) progress being made as expected? (with respect to life support functionality) | The DSS shall incorporate LSS data values with timeline specific context | Compare estimates of predicted LSS data with performed data within the context of timeline activities | This requirement aims to associate unique timeline constraints with forecasted operability of the LSS. The remaining tasks demand time and resources, and the LSS must support those actions. Right now, the limiting consumables are tracked in real-time using some basic averaging calculations based on O2 usage, but what if we could forecast more accurately the anticipated task demands on the LSS? In broad terms, the remaining tasks cumulatively require some amount of time to complete. Conversely, the LSS can provide some finite amount of time to operate. This timeline margin therefore becomes the overall constraint on EVA operations. This overarching constraint is a fundamental constraint of EVA operations and must be accurately estimated throughout EVA execution. |
| LSS - 22 | What tasks (and constraints) are remaining and can my LSS support those tasks? | The DSS shall associate LSS constraints with remaining timeline tasks | Estimate LSS performance in comparison to expected LSS performance for the remaining timeline tasks | In conjunction with LSS-20, not only is it important to capture LSS performance as associated to as-performed timeline execution, it will be important to also built forecasting capabilities based on that data. This type of analysis is aimed to help promote more advanced forecasting capabilities so that the demands on the LSS can be predicted can be appropriately estimated for upcoming timeline execution. |
| LSS - 23 | Is the crew/system prepared for the subsequent states (steps in the timeline)? | The DSS shall estimate the feasibility of future components of the timeline based on real-time projections of LSS states | Compare projected estimates of LSS data with predicted estimates | Knowing what has been done and what is currently being performed from a LSS performance perspective is important. But we also have to consider what we are about to perform. This requirement emphasizes the forecasting capability of LSS states. What immediate demands will be “loaded” onto the LSS to complete the subsequent tasks? Will there need to be alternate tasks performed to maintain adequate life support such as O2 recharge? What timeline implications will that impose on subsequent tasks? |
| LSS - 24 | What is the state of affected systems/ hardware? | The DSS shall track the operability of LSS | Assess whether the LSS can perform in an expected/ acceptable fashion | Operability is a key system state during operations. This requires an understanding of the interplay of internal system variables and environment variables. For example – an ammonia leak from ISS hardware can require clean-up/bake-out time procedures if the spacesuit becomes contaminated. This requirement also leads to capabilities such as overlaying complementary data sets to search for deviations that may indicate operability degradations. This requirement also introduces perspectives such as observability of systems to make such operational assessments. |

Table A.7: Decision ladder results for LSS - Ambiguity stage

## LSS - Ambiguity

| ID | SME State of Knowledge (SoK) | Cognitive Work Requirements (CWR) | Information Relationship Requirement (IRR) | Requirement Intent |
|---|---|---|---|---|
| LSS - 25 | What are the forecasted estimates of consumables? | The DSS shall estimate the affordances of LSS consumables for the remainder of EVA timeline | Calculate, based on performed LSS data, an estimate of consumable affordances (see forecast techniques) | Projecting what limitations may appear at a future point in time and space is a major focus of attention. Within the EVA domain, the life support system can only sustain operations for a finite amount of time. But more generally, timeline limitations may not be the only constraint. Task options or procedure inhibits can play an important role in impacting life support system performance. Additionally, some LSS consumables are replenishable and some are not. To complicate matters, future spacesuit designs have not been finalized so the final set of consumable variables may differ from present-day systems. Regardless, knowing how close the LSS is to their engineering and operational limits is paramount to ensuring successful timeline execution. |
| LSS - 26 | What information is needed to assess successful task completion? (in terms of exertions levels, functioning hardware) | The DSS shall assess auxilary information to incorporate into LSS assessment and forecast calcualtions | Prioritize LSS information to discrimenate major contributing factors to LSS estimates | Even after extensive training and preparation, how the crew perform on the day of execution will only become apparent once they have done it. Furthermore, systems outside of the EVA domain may have significant impacts on LSS performance which also may not be known until the EVA is being executed. The airlock for example has direct interfaces with the LSS. Therefore, airlock systems will need to be ready in order to interface properly with the LSS system. Auxiliary systems in this context refer to all other systems that can influence LSS operability. The inclusion of these systems must be taken into account to address whether actions are actually feasible. Flight rules can help articulate the acceptable conditions but the number of systems can quickly increase since crew exist and work on an entirely engineered system. |
| LSS - 27 | Can the current timeline be maintained from a mental/physical fatigue/ injury posture? | The DSS shall assess future timeline LSS demands alongside forecasted estimates | Calculate any discrepancies in feasible task distributions based on forecasted LSS performance | This requirement is intended to capture the non-traditional sensor data that can impact LSS performance. Knowing what the demands will likely be in terms of LSS operability will help with forecasting. A simple example includes a translation vs. stationary task on ISS. Translations has higher periods of stress on the system (e.g. higher met rates and consumables usage) as opposed to stationary tasks. Having the system know what is likely about to occur can help with internal sense-making as to failures and usage concerns. The challenge here is that there are no direct measures that a system can meaningfully interpret. The ambiguity arises from the largerly qualitative data set that is typically used to make these particular assessments. |
| LSS - 28 | What is the current and potential timeline margins given the current state of the crew/ system functionality? | The DSS shall estimate the feasible distributions of tasks, given the timeline execution performance of the life support systems | Estimate the measure of carrying capacity of the limiting consumables to meet the remaining timeline tasks, accounting for historical life support system and related task performance data | Knowing how you fare in relation to consumable margins is paramount to making informed decisions about timeline execution. At first pass, feasibility can be considered as the assessment of time available to complete the remaining planned tasks. But we can immediately extend this to considering alternatives and whether those alternate timeline designs meet the “in-the-moment” consumable limits. We can extensively leverage historical data to provide a robust baseline for comparison of tasks. These may also lead to the application of machine learning algorithms to assess aggregate historical trends. Making this assessment though is no trivial feat and will require an extensive consideration of the contextual features of both the LSS system corrolated with the timeline details to support both timeline execution as well as timeline alteration 'what-if' analyses. |
| LSS - 29 | What is the risk posture associate with getting the crew to a safe configuration of crew/ vehicle/hardware/ resources? | The DSS shall generate and manage the what-if scenarios resulting from the performed LSS data | Calculate potential what-if scenarios as potential alternatives/solutions to advance the timeline, given the performance of the LSS | Risk management is a constant consideration during EVA execution. Every action has some amount of risk associated with it. The planned timeline has contained within it an agreed upon level of risk (which is why in part the timelines take so long to make). However, if we begin to deviate from the plan, we expose the crew to additional risks. Currently, flight rules are currently used to implement the a priori agreed upon the minimum risk actions but what happens when you get into situations that are unscripted and beyond what the flight rules specify? Knowing how the LSS system will likely perform in degraded states will be important to facilitate so that more realistic what-if scenarios or alternatives can be explored. Coping with potential multi-path options simultaneously could have value in addressing the ambiguity but could add significant demands to the cognitive capacities of the crew. |
| LSS - 30 | What is the risk posture associate with getting the hardware/systems to a safe configuration? | The DSS shall generate and manage the systems' specific what-if scenarios while incorporating LSS data | Calculate potential what-if scenarios as potential alternatives/solutions to advance the timeline, given the performance of the LSS | Complementary to LSS-29, similar considerations will need to be make about protecting systems themselves when they degrade. This requirement attempts to highlight the challenges that will need to be considered with all the custom hardware that will be with the crew and their ability to maintain that hardware while contending with their own LSS performance capabilities. Perhaps in the future, other hardware systems will be able to tend to hardware anomalies but under present-day and historical precedence, the EVA crew are prime actors in maintaining hardware. |
| LSS - 31 | What are the potential caution/hazards to task execution? (Anticipate hazards/consumption rates for subsequent steps) | The DSS shall incorporate known caution/harzards into the LSS assessment | Compare LSS system data to known cautions and hazards indicated in the EVA timeline | Flight controllers purposefully design timelines to cope with the hazards that will inevitably be present during operations. They try to minimize these periods of hazardous activity and try to anticipate all failure modes. We need to work towards characterizing these risks in association with timeline elements. Knowing where break out/in points exist are key to coping with hazards that escalate beyond acceptable levels. Cumulative effects of hazards can impose higher risks. The uniqueness of these hazards currently enforces a high level of scrutiny of EVA execution by teams of flight controllers to catch these potential hazards and its escalation early so that they cab be dealt with. without jeopardizing the mission. |

Table A.8: Decision ladder results for LSS - Goals stage

## LSS - Goal(s)

| ID | SME State of Knowledge (SoK) | Requirement Intent |
|---|---|---|
| LSS - 32 | Return the crew back to the spacecraft safely (not just alive but also functional) | When we consider the goals of life support system management, two perspectives are important: We need to return the crew back safely (not just in an absolute sense, but in a functional state). At the highest level this means that the crew arrive back in a healthy state with functioning systems that fall within the consumables margins afforded by the LSS. The `functional' component of this goal is that the hardware/systems as well as the crew return in state that is not degraded beyond repair. |
| LSS - 33 | Meet the objectives of the EVA so you don't incur the risk of performing an unscheduled EVA | The second goal, and 2nd in priority, is the aim to meet the intended objectives of the EVA so the risk of a subsequent unscheduled EVA is limited. This links back to the perspective that each EVA has very specific purposes and when those objectives are not met, that can impact future operations. This requirement emphasizes getting as much productivity from the crew as possible while outside the spacecraft, so that unplanned operations with higher risks are not necessary later. |

Table A.9: Decision ladder results for LSS - Ultimate Goals stage

## LSS - Ultimate Goal(s)

| ID | SME State of Knowledge (SoK) | Cognitive Work Requirements (CWR) | Information Relationship Requirement (IRR) | Requirement Intent |
|---|---|---|---|---|
| LSS - 34 | Does the current timeline maintain crew/vehicle safety? | The DSS shall incorporate relevant safety metrics to assess crew safety throughout the timeline | Assess the performed state of LSS operational margin in comparison to allowable specifications | One of the immediate goals of LSS management is ensuring a safe operational environment during timeline execution. This requires knowing what definitions of safety are important to consider and assess. More emphasis needs to be placed on specifying what these safety metrics are and how they might be acquired/synthesized. |
| LSS - 35 | Does the current timeline achieve the desired EVA task priorities? | The DSS shall assess performed timeline progress within the context of planned timeline elements | Assess the progression of timeline execution in relation to planned timeline activities -> Objectives | In general, real-time operations involves assessing the safety on a “moment by moment” basis to acquire a collective sense of system safety during task execution. The system will therefore need to be able to synthesize timeline progress and relate that data to the planned timeline characteristics, particularly related to planned LSS performance trends associated to specific timeline elements. |
| LSS - 36 | Does the current timeline accommodate the current state of the crew/system state? | The DSS shall assess the performed timeline progress within the context of LSS capability | Assess the overall likelihood of success in achieving the timeline objectives based on LSS performance (performed/projected) | Additionally, there is the intent of comparing and assessing LSS performance specifically related to overall functionality and capability. The priority here is to know what has happened, what is happening to know how LSS might perform in the near and far future. This will require both a synthesis of historical data but also comparison to actual/planned data used to address LSS-34. |

Table A.10: Decision ladder results for LSS - Goal State stage

## LSS - Goal State

| ID | SME State of Knowledge (SoK) | Cognitive Work Requirements (CWR) | Information Relationship Requirement (IRR) | Requirement Intent |
|---|---|---|---|---|
| LSS - 37 | Should(does) information be requested/relayed? | The DSS shall provide relevant/ desired LSS information and the capability to relay that information | Manage and transfer desired LSS content to appropriate operators/systems | Since information is distributed throughout the domain, the exchange of relevant information is a vital component of reaching a desired goal state. The facilitation of that exchange is what the DSS should help with. Expectations of where and in what form this LSS data and how it might be exchanged is yet to be defined. |
| LSS - 38 | Should the timeline be altered? | The DSS shall incorporate timeline alterations | Track/manage timeline alterations and the associate LSS implications associated to those changes | Related to timeline elements, should they be altered and to what end -state should be reached is what this set of requirements attempts to convey. A constant reminder of this goal is that "Flight plans are only good at the start of day one." Alternations are inevitable, but what alterations need to be made and how those changes will be implemented and executed is an open area of investigation. |
| LSS - 39 | Should systems states be altered? | The DSS shall assess and control (influence) LSS system states | Send/receive command and control direction of LSS configurations | Additionally, systems states may need to be altered to reach a particular ultimate goal. How might we go about controlling system states needs to be considered early in the design process. We can't leave the individual technical stakeholders to decide how systems states change at an individual level, this needs to be managed at a higher operational level to make sure we are satisfied with how the collective systems' states may change and be controlled. Mode control from air traffic control operations might be useful concept to be applied here. |
| LSS - 40 | Should resources be redistributed? | The DSS shall assess the distribution EVA resources | Assess/manage the distributions and potential redistribution of resources (e.g. geospatial, variable quantity) | Finally, with timeline and system elements, there are the assets and resources that must be distributed appropriately to enable timeline progress. Alterations will imply that assets/resources may have to be redistributed in order to meet task demands. |

Table A.11: Decision ladder results for LSS - Task stage

## LSS - Task

| ID | SME State of Knowledge (SoK) | Cognitive Work Requirements (CWR) | Information Relationship Requirement (IRR) | Requirement Intent |
|---|---|---|---|---|
| LSS - 41 | What information/resources are needed and how do they become accessible? | The DSS shall identify and assign relevant resources | Mange and control appropriate resources for implementation | The actions pertaining to information accessibility will be a complicated exchange between various sources of data (e.g. audio from the crew, text from MCC and data displays). Meeting these requirements will require a close examination of the expected work to be performed and hypothesis-driven exploration of what tasks might be conducive to supporting those work goals. One example is the acquisition of vehicle systems states, to relate to EVA operations such as recharging of O2. Recharging O2 will require the availability of vehicle systems states, in addition to spacesuit information. |
| LSS - 42 | What procedure needs are present and how are they accessed/applied? | The DSS shall associate information/resource needs with associated detailed procedures/ instruction | Integrate detailed procedures with real-time information and resources statuses and identify incompatiable procedure sequences | Procedures will undoubtedly be a part of future operations. The challenge will then become the applicability, accessibility and implementation of those steps for the crew to perform. Here, the requirements identify the need to have operational context to help guide the applicability built into the system, so that procedures can be applied when needed and performed. There will also be the need to know when procedures may be no longer applicable depending on the actual context of use. This includes tasks such as standard contamination procedures or other suit anomaly procedures. |
| LSS - 43 | What needs to be completed to advance the timeline (elements to consider: task execution pacing, resting, replenish consumables, etc.) | The DSS shall incorporate timelines elements in order to progress the timeline (LSS specific elements) | Integrate various timeline phases based on EVA objectives to ensure sufficient progress is being met | Finally, EVA productivity is centered around the tasks needed to be performed. The LSS system must integrate the specific task demands its systems will require to ensure overall timeline progress is being met. For example, if there is a contamination leak, additional contaminations procedures related to the LSS must be integrated to the timeline to ensure safe continued operations. There must be a closer synchronization of LSS performance criteria with the timeline to assist with this integration endeavor. |

Table A.12: Decision ladder results for LSS - Procedure stage

## LSS - Procedure

| ID | SME State of Knowledge (SoK) | Cognitive Work Requirements (CWR) | Information Relationship Requirement (IRR) | Requirement Intent |
|---|---|---|---|---|
| LSS - 44 | What set of procedures should be used to advance within the timeline? (are there any deviations that must be incorporated?) | The DSS shall associate detailed procedures and manage deviations applied to those procedures | Manage the modification and integration of procedures prior to/during/and after execution | At this stage of the DL, the exact specification or method of implementation becomes hypothetical. The intent at this stage is to consider the ramifications of the specific work practices we envision with the future crew/system team. The act of actually carrying out these procedures will be an evolving hypothesis about what is considered a reasonable work environment. Only by systematically prototyping and testing future systems within an envisioned context can this stage of the DL be realized. |
| LSS - 45 | How should those procedures be developed, accessed, and utilized? | The DSS shall manage the interdependencies between procedures | Integrate the interdependencies between procedures and system states to ensure compatability | |
| LSS - 46 | What are the new forecasted consumable capabilities based on the application of the procedures? | The DSS shall update LSS forecasts based on timeline alterations | Track and project LSS forecasts based on performed and projected consumables usage | |
| LSS - 47 | What information/resources are needed to advance within the selected set of procedures within the timeline? | The DSS shall present the relevant timeline elements within the context of timeline progression | Manage the interaction and display of LSS/ timeline elements within the context of EVA execution | |
| LSS - 48 | What additional information/resources are required to advance future components of the timeline? | The DSS shall provide the flexibility to incorporate auxiliary (new) information into timeline projections | Integrate auxillary information into future timeline elements to better forecast LSS performance | |

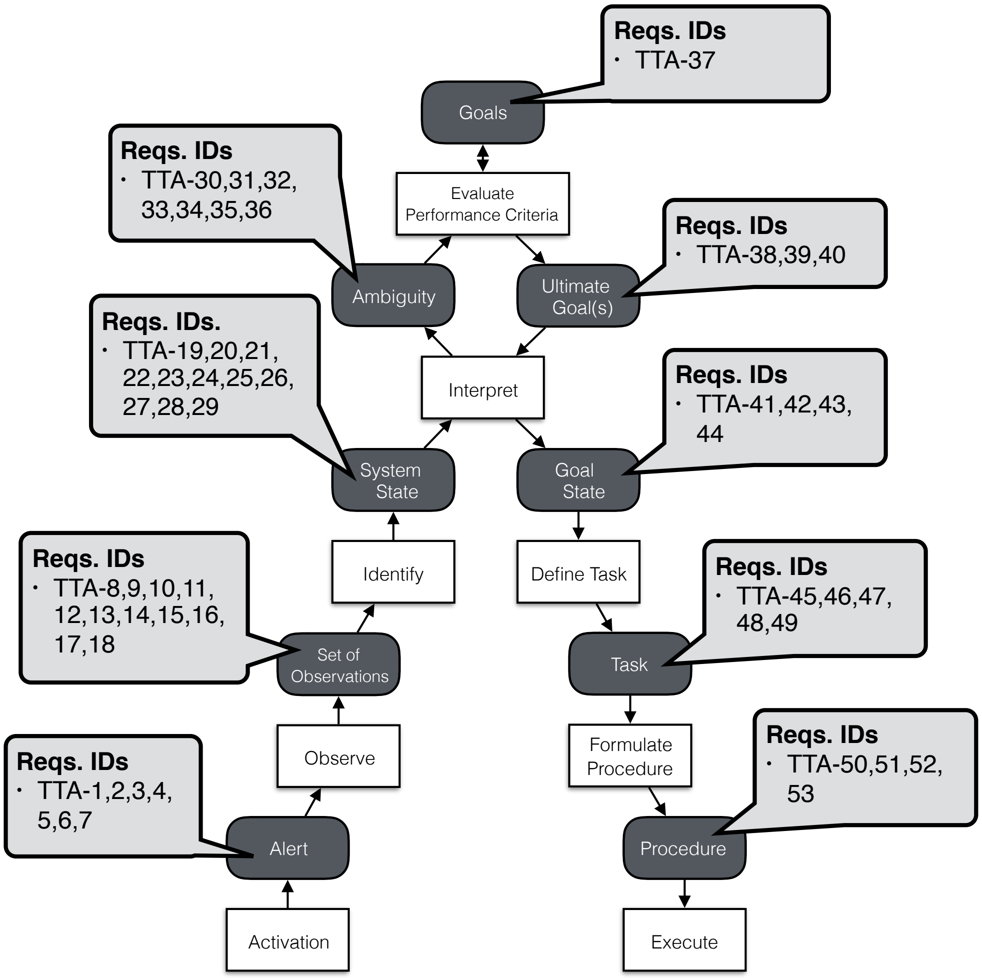


Figure A.7: Decision ladder summary of results for timeline tracking and alteration (TTA).

Table A.13: Decision ladder results for TTA - Alert stage

## TTA - Alert

| ID | SME State of Knowledge (SoK) | Cognitive Work Requirements (CWR) | Information Relationship Requirement (IRR) | Requirement Intent |
|---|---|---|---|---|
| TTA - 1 | Timeline progress (in terms of deviation from planned - ahead/behind) | The DSS shall calculate the timeline posture of the EVA throughout the duration of the EVA | Compare the tasks performed to the tasks planned both in terms of activity and temporal sequence | The ability to track timeline progress requires the ability to signal when deviations from expected progress takes place. Deviation can occur both in the execution of tasks themselves and the temporal sequence of events. Difficulty arises when crew are in the middle of an activity with no clear reference points within a defined period of time to establish where exactly the crew are in the timeline. Timeline tracking must incorporate the appropriate level of granularity to have a refined understanding of timeline progress (e.g. ahead, behind, on schedule and by how much?). |
| TTA - 2 | Hardware anomaly | The DSS shall incorporate hardware anomalies into the management of the EVA timeline | Track/calculate system hardware anomalies to other required systems for timeline execution | Hardware anomalies will be a critical element to incorporate into timeline management. However, the hardware to be used in the future is currently ill-defined for future missions which makes it difficult to specify what hardware anomalies could potentially exist. Hardware is a generic term here that includes but is not limited to spacesuit, tools, vehicle, and other infrastructure. Coupled with this requirement is the aim to associate timeline elements with the implications of hardware anomalies. For instance, if a particular task requires a certain hardware capability and that capability is degraded, the crew will need to potentially find alternative tasks or tools to achieve a particular goal. |
| TTA - 3 | Procedure anomaly | The DSS shall incorporate procedure execution anomalies into the management of the EVA timeline | Compare as-performed procedure execution to the planned procedures | Procedure anomaly management should not only be able to handle in the moment-by-moment errors that arise but also flag deficiencies for subsequent downstream procedure execution. Anomalies can include the incorrect execution, omission, and/or partial completion of procedures as defined in the timeline. What implications does an anomaly now imply about the timeline tasks an hour or two hours in the future? And just as important, how do you go about rectifying those procedures to make them compatible? This should be a near-term development effort to handle this type of alert. |
| TTA - 4 | Environment change | The DSS shall incorporate environmental changes into the management of the EVA timeline | Compare acceptable environmental values with real-time data values | ISS environment contends with Low-Earth orbit (LEO) conditions such as varying thermal and lighting conditions. Additionally, crew operate on and around the ISS on engineered surfaces that present engineering hardware constraints. For planetary 'natural' surfaces, we need to consider environmental conditions both locally and globally, space weather, we well as external/internal suit environments. Near term development makes sense once we start focusing on particular destinations. The following documents describe the environmental of the natural environments of potential mission destinations.  o Engineered environments in Low Earth Orbit: (Coan & Bell, 2012; Coan & Kagey, 2005; Dutton, 2011; Heckman, 1974; Ross, 1994; Thuot & Harbaugh, 1995); Lunar: (Meuller, 1966) (Wortz, 1969) (Seminara & Shavelson, 1969); NEO/Asteroid: (LeCompte, Meyer, Horsewood, McKay, & Durda, 2012; Steinberg, Kundrot, & Charles, 2013); Mars: (Conley & Rummel, 2010; Hill, McFarland, & Korona, 2013; Kaplan, 1988; Marquez & Newman, 2006; Vasavada et al., 2012); Mars Moons: (Abercromby, Gernhardt, Chappell, Lee, & Howe, 2015; Goswami et al., 2012); Space in-general: (Irons et al., 1994; Irons, Eberhardt, & Schulz, 1992; Khan-Mayberry, James, Tyl, & Lam, 2011; Taylor, 1973; Tremblay, 1994) |
| TTA - 5 | Inhibit conflict | The DSS shall incorporate inhibit conflicts into the management of the EVA timeline | Manage the impact of inhibit conflicts as it relates to timeline execution | An inhibit is defined as the implementation of a control mechanism to a safety hazard through mechanical, electrical, and/or software restrictions. Inhibits are more broadly invoked for timeline progress from a systems perspective (think systems configurations) to ensure procedures are safe to perform. Additional associated should include how to implement an inhibit (that is or is not applicable) with implications to task execution progress and procedure details. |
| TTA - 6 | Crew input | The DSS shall incorporate crew input/feedback into the management of the EVA timeline | Manage crew input to adjust a priori task execution estimates within the timeline | Crew are considered a vital 'sensor' during EVA. Crew input is highly valued and utilized to assess what systems configurations actually are and how tasks are actually being performed. Crew also provide a variety of insight into system functionality and on-going task/system progress/status. The intent of this requirement is to acknowledge that crew audio input is highly valued during EVA operations and future support systems should aim to utilize this source of data effectively. |
| TTA - 7 | Time window constraint violation | The DSS shall incorporate time window constraints into the management of the EVA timeline | Manage timeline time window constraints with crew task execution progress | Many of the tasks performed during EVA have associated time window constraints. This means that tasks can only be executed during these windows of opportunity. Examples include but are not limited to thermal, bake-off, and time to activate limits. These are all 'time to effect' constraints that are typically known a priori that must be adhered to for safety or operational constraints. Other examples include tasks that can only be installed on the ISS in dark/light cycles. |

Table A.14: Decision ladder results for TTA - Sets of Observations stage

## TTA - Set of Observations

| ID | SME State of Knowledge (SoK) | Cognitive Work Requirements (CWR) | Information Relationship Requirement (IRR) | Requirement Intent |
|---|---|---|---|---|
| TTA - 8 | What is the current timeline position? (time & geospatial distribution of resources and assets) | The DSS shall track the position of the crew within the timeline both temporally and geospatially | Calculate the deviations between the geospatial and temporal data values of the crew to the planned timeline | Knowing where you are in the timeline requires two primary categories of data: Temporal and Geospatial. In other words, are you on schedule in terms of time and are you actually located where you intended to be located in the sequence of tasks? In other words: what are the crew doing, when are they doing it, and where are they doing it. All this observational data should reference to the planned timeline. NOTE: the planned timeline can change and therefore your reference data is also changed. The emphasis here is that both temporal and geospatial information must be related to a scripted plan for comparison to estimate overal timeline position. |
| TTA - 9 | What is the geospatial location of the crew/ assets/resources? | The DSS shall monitor the geospatial distribution of assets and resources included in the EVA timeline | Estimate the geospatial distribution of assets as they relate to the crew and measure accessability to those assets | Not only do you need to know where everything is situated relative to the timeline, you also need to know how resources are distributed geospatially in relation to the vehicle and crew. But even if you know where everything is physical located, other parameters are important to consider such as asset accessibility. Additionally, configuration status is also important to know how to access a particular resource. Resources in this context can include tools, hardware, rechargeable consumables, and payloads. Currently, DOUG (Dynamic Onboard Ubiquitous Graphics) is used to visualize geospatially the crew and assets on the ISS but is used primarily for planned purposes rather than real-time assessment. Additional development perspectives can be made on the geospatial visualization and planning by referencing the following works: (Carr, Newman, & Hodges, 2003; Marquez, 2007; Marquez & Cummings, 2008; Marquez & Newman, 2006) |
| TTA - 10 | What support is required to execute the current detailed procedure? | The DSS shall manage the procedure support needs of the crew for all phases of the EVA timeline | Track and forecast detailed procedure needs during real-time task execution | This requirement is meant to emphasize the ‘moment-by-moment’ support which is highly task dependent. The associated amount of task instruction and detail will need to be included for each task in the timeline. How can we provide the crew with the support features needed to accurately execute the detailed procedures? The range of specificity in task detail can vary dramatically. Therefore, the necessary task support and the associated success criteria (See TTA-13) must be defined and made available for use during operations. |
| TTA - 11 | When/where are the potential break-out points in the detailed procedure? | The DSS shall manage the regions of the timeline to safely break-out and resume procedures | Track and associate real-time task execution in relation to acceptable break-out (break-in) points | This is intra-task information related to what would be considered acceptable ‘break-in’ and ‘break-out’ points. Another name for this concept is known as 'bingo times'. Sudden breaks in procedures or deviations (intended or unintended) can cause a reintegration of tasks and force modifications to procedures to occur during execution. All implications of those altered start/stop configurations need to be fully understood to ensure compatibility. Bingo points assist both in projecting forward to understand future implications of procedure anomalies but also works backwards when you have to go-back or revisit a procedure that was skipped earlier. Additionally, these points should include considerations of cut-off points to proceed to the next set of mission objectives. |
| TTA - 12 | What are the constraints of the remaining tasks (procedures, hazards, location, interrelations between tasks, environmental acclimatization, etc.) | The DSS shall manage the constraints associated with tasks within a timeline | Track and integrate task constraints during real-time operations | Examples of task constraints can include: inhibits, hardware limits, thermal windows, power constraints, mechanical constraints. Even the ability to exchange information between EVA members can be considered with task constraints. For instance, if a known Loss of Signal (LOS) is about to occur, ensuring the transfer of information between crew members so they know what they must do during audio dropout is required. Note that these constraints are dependent on the objectives/ tasks specified in the timeline. Future missions will include primary science objectives and tasks which will benew and uncharted territory in terms of attributes within the EVA work domain. New scientific task constraints are inherently tied to the science objectives being addressed and future work will be required to operationalize the constraints of those particular tasks. |

Table A.15: Decision ladder results for TTA - Sets of Observations stage continued

## TTA - Set of Observations Continued

| ID | SME State of Knowledge (SoK) | Cognitive Work Requirements (CWR) | Information Relationship Requirement (IRR) | Requirement Intent |
|---|---|---|---|---|
| TTA - 13 | What information is needed to assess successful task completion? (verification and validation) | The DSS shall manage the verification and validation to determine successful task completion | Track and catalog task execution progress and compare that to presupposed success criteria | Not only does the system need to be aware of constraints and their implications for successful execution, the DSS needs to also be aware of the information necessary to consider a task successfully complete. Currently, we rely on video of the crew performing the task, and verbal confirmation. For systems that integrate with the ISS, system diagnostics is sometimes performed by ground personnel to check for proper functionality. How we go about defining verification and validation criteria for task execution will be paramount to tracking desired crew progress. |
| TTA - 14 | What are the relevant flight rules pertinent to the tasks being performed? | The DSS shall incorporate context specific flight rules to the EVA timeline | Manage and relate relevant flight rule constraints during real-time execution | Flight rules govern many of the operational behaviors of the crew. The DSS needs to be aware of what flight rules are currently in effect and be able to enforce those rules that are contextually relevant during execution. What happens when a flight rule does not exist or there is a flight rule conflict? Currently, ground support personnel dedicate a non-insignificant amount of time determining the applicability of flight rules and their implications. While flights rules are intented to be clear, the particularities of each EVA can make the applicability of flights rules nonobvious. Future missions will also likely contend with a host of new kinds of flight rules that govern scientific operations. What does science related flight rules look like and how will they influence operations? |
| TTA - 15 | What is the prioritization of the remaining tasks? | The DSS shall manage the prioritization of timeline tasks based on a priori and real-time input | Manage (prioritize) timeline tasks in relation to presupposed timeline objectives | Task prioritization is imbedded within the planned timeline. Priorities are typically preloaded and scripted prior to execution. However, as the timeline is executed, priorities can change based on actual progress to meet overall timeline objectives. This shifting nature of priorities and their applicability and their likelihood of completion will need to be considered for future missions. |
| TTA - 16 | Where are the potential operation caution/ hazards to task execution? | The DSS shall incorporate operational notes/cautions/warnings during task execution | Manage (incorporate) relevant notes/cautions/ wanrings during task execution | Associated with each task there is always an inherent amount of risk. When that risk is high enough (which is usually considered prior to task execution) notes/caution/warning messages are imbedded into the timeline. The inclusion and presentation of this specific information at appropriate times is important to ensure safe operations. |
| TTA - 17 | What are the potential environmental caution/ hazards to task execution? | The DSS shall incorporate environmental constraints during task execution | Compare environmental constraint values to acceptable presupposed values | Knowing the environmental states surrounding the crew/vehicle are important to ensure a safe work environment How might we support this environmental monitoring? Environmental constraints considered in other work domains such as air traffic control could provide some structured insight to guide development efforts towards satisfying this requirement (Ahlstrom, 2005; 2015; Durso & Manning, 2008). |
| TTA - 18 | What are the present indicators of identified anomaly? | The DSS shall trace and manage indicators of task/procedure anomalies | Track deviations and anomalies from task/ procedure execution | Finally, indicators of the anomaly (if they exist) need to be made apparent to the crew. This comes in two forms, there could be an indicator of a 'potential' anomaly (one that isn't quite as serious but could indicate a larger problem could occur) and an actual anomaly (what do we actually do with an actual anomaly). Future crew will need support managing both forms. |

Table A.16: Decision ladder results for TTA - System State stage

## TTA - System State

| ID | SME State of Knowledge (SoK) | Cognitive Work Requirements (CWR) | Information Relationship Requirement (IRR) | Requirement Intent |
|---|---|---|---|---|
| TTA - 19 | Is the task (procedure) progress being made as expected? | The DSS shall assess task execution progress in relation to the planned timeline | Associate timeline execution progress in relation to planned performance | There is a temporal and 'task success criteria' component to this requirement. Temporal in this context is meant to determine whether the tasks are being performed at the expected times. In addition, the success of task execution must be assessed. But what defines task success? The minimum success criteria will need to be defined for timeline task completion which is tightly related to the type of task being performed. Currently, completion of all specific task steps implies that the success criteria is met, but what happens when some of the steps cannot be completed due to unforeseen circumstances or success criteria are somewhat ill-defined? Every EVA task has some form of 'success criteria' that will need to be met that signifies the task has been successfully accomplished. |
| TTA - 20 | Where is the timeline progress in relation to the break-out and catch-all points? | The DSS shall manage the relation between timeline progress and break-out (catch-all) points | Track and associate real-time task execution in relation to acceptable break-out (break-in) points | These breakout points are critical for situating where potential alterations are feasible. Crew progress in relation to these points of known impact (e.g. systems are in a safe and desireable configuration) will be useful moving forward when alterations need to be made. In general, this system state understanding strives to provide a reference point to start that alteration process (if needed) |
| TTA - 21 | What are the applicable crib-sheet procedures (are they still valid?) | The DSS shall assess the appropriate crib-sheet procedures, given the current state of timeline progress | Associate task execution progress with appropriate crib-sheet procedures | On-demand cribsheets will be a vital component of task detail that informs how task execution may evolve . These are particularly important for tasks involving engineered systems where the hardware does not behave or configure as expected. The cribsheets become a bit more abstract when it comes to science related tasks or work on natural surfaces since that information is typically not known a priori. At the very least, any cribsheets that are relevant to the tasks at hand should be readily accessible if required. The DSS can get rather advanced with this requirement if you start bringing in natural language to recognize which line item in the crib-sheet is needed. But at the very least the entire set of cribsheets should be able to be parsed based on the task being performed and presented to the flight team for implementation. Another nuance of this requirement is the concept of validity. Can the system know or parse out cribsheet notes that no longer apply? |
| TTA - 22 | Is the crew/hardware prepared for the subsequent timeline tasks? | The DSS shall assess the availability of resources required to complete subsequent tasks | Calculate the availability in terms of system readiness, accessability to the crew and overhead required to implement the tool/system in relation to current crew progress within the timeline | This requirement pertains to the preparatory assessments required to perform a task. All tasks will require resources, such as a hammer, tool kit, or some kind of expendable device etc.. Knowing those assets are accessible and in a proper state of functionality will be paramount. The vision here is that the DSS should be aware of the necessary demands for upcoming timeline tasks. The difficulty with this aim is how to network all these 'dumb' assets in a way that can have a DSS aware of their location, configuration, status, etc. on demand. This requirement borders with the Inventory management work function to some extent but the key is to link this management with the timeline task itself as the timeline is executed to provide that real-time support. |
| TTA - 23 | What is the mental/ physical state of the crew members? | The DSS shall integrate crew mental/physical health into timeline tasks to assess execution capability | Assess crew mental/physical health in relation to acceptable limits for task execution | The mental/physical health of the EV is currently an abstract measure that is assessed through tone of voice, language, and speech patterns. Currently, ground support personnel rely on deviations in these voice characteristics while the crew execute the timeline to help indicate what the mental/physical state is. There could be potential solutions from the world of speech pattern recognition: (Greeley et al., 2006; Krajewski, Wieland, & Batliner, 2008). This assessment is a longer term assessment over the course of the EVA. This requirement is a companion requirement to TTA-22 to help determine whether the crew can successfully complete future tasks in the timeline. |

Table A.17: Decision ladder results for TTA - System State stage (continued)

## TTA - System State Continued

| ID | SME State of Knowledge (SoK) | Cognitive Work Requirements (CWR) | Information Relationship Requirement (IRR) | Requirement Intent |
|---|---|---|---|---|
| TTA - 24 | What is the operational state of the EMU (as it is related to the tasks being performed)? | The DSS shall integrate LSS data to ensure system functionality for task execution | Associate limitations in life support system performance to allow task execution | This requirement related directly to the status of the EMU and the anticipated requirements/demands of the EMU on the upcoming tasks. For instance, if the upcoming task will be a very demanding task from an EMU performance perspective, the DSS will need to know if the EMU can support those tasks. Maybe there is an alteration or break to be inserted to prevent subsystems from becoming saturated or keeping the system within safe operational limits? At the very least, the system needs to be aware of total life support giving capability to know that the crew can stay alive and complete the planned timeline. |
| TTA - 25 | What is the current redundancy posture for critical systems? (risk vs. task priority/ criticality) | The DSS shall manage the redundancy status of systems integral to the completion of tasks and weigh them in relation to task priority/criticality | Assess the redundancy posture of task critical hardware to ensure execution capability | There is a tradeoff to assess the redundancy level of systems during execution. Do you press on a task with no fault tolerance and run the risk of not completing the task or do you drop the task and trying doing it later within more levels of fault-tolerance can be obtained? Again, this is highly dependent on the hardware and task being performed, but this is a relevant question to address and one that a DSS must be capable of handling. Redundancy links directly to successful task execution potential and the crew need to be aware of the states of these systems they are working with. |
| TTA - 26 | Are known caution/ hazards accounted for? | The DSS shall manage the known caution/ hazards in relation to as performed task execution | Manage (incorporate) relevant notes/cautions/ wanrings during task execution | Peppered throughout the timeline are relevant notes/cautions/warnings that need to be implemented at appropriate times. Typically, they are refreshers for the crew to make sure they do something correctly. Highly task/configuration dependent but the system should be able to manage and apply those elements based on the progress of the timeline. |
| TTA - 27 | What is the extent of any anomaly, if present? | The DSS shall integrate anomaly data for troubleshooting and problem diagnosis | Calculate diagnosis and anomaly resolution options to assist in troubleshooting | This requirement has some cross-over with the anomaly response and resolution work function. However, this requirement is trying to say the DSS should be able to handle troubleshooting and problem diagnosis as it relates to timeline task execution. Additionally, there exists some cross-over with incorporating cribsheets capabilities since that is usually the first level of anomaly response. Can the system somehow ingest anomaly data and help facilitate the diagnosis and response process? |
| TTA - 28 | What are the forecasted affordances in consumables? | The DSS shall integrate forecasted consumable affordances with as-performed and projected timeline tasks | Calculate the forecasted affordances of consumables and relate to projected timeline elements | This is the primary requirement in assessing overall timeline tracking. In this case, the system knows what has been performed and (assuming a nominal completion to the planned end) can forecast the end state of the timeline in terms of time. This information can then be associated to the limiting consumable forecasts that are currently based on consumables usage rates from the life support system. There is a lot of room for improvement here because currently, this integration progress is a manual process that involves numerous EVA console positions. |
| TTA - 29 | What is the current mental/physical state of the crew members? (e.g. task overload, fatigue, etc.) | The DSS shall assess physiometric data to assess the mental/ physical state of the crew in relation to task demands | Assess crew mental/physical health in relation to acceptable limits for task execution | How can we assess the current physiological data to understand crew mental/physical state? The Flight Surgeon/BME console will need to be consulted to investigate this requirement in more detail. Currently EVA flight controllers only consider metabolic rate for performance assessment. Audio communication is also used to qualitatively assess crew health status. [Refer to the EVA informatics research efforts] |

Table A.18: Decision ladder results for TTA - Ambiguity stage

## TTA - Ambiguity

| ID | SME State of Knowledge (SoK) | Cognitive Work Requirements (CWR) | Information Relationship Requirement (IRR) | Requirement Intent |
|---|---|---|---|---|
| TTA - 30 | Can the current timeline be maintained? | The DSS shall integrate task execution progress to assess the likelihood of successful task execution | Calculate the likelihood of successful execution of future tasks based on timeline progress | The likelihood of task completion can be thought about in two conditions: an absolute and probabilitic assessment. In an absolute sense, remaining planned timeline can be quantified to assess the feasbility of the remaining tasks to be performed. If there isn't enough time, more time could be add or tasks could be dropped. A more probabilistic approach can also be utilized which can include historical data to help estimate whether the crew have historically completed the planned tasks in the allotted time. Currently, probabilitic assessments are fuzzy estimates based on limited historical training and actual task execution. In either case, the system should have a capability to anticipate how the crew will perform based on how the timeline is currently being performed. The intent here is to provide a more realistic estimates for potential (feasible) timeline alterations. |
| TTA - 31 | Are there any alternative timeline options available? Is so, which alternative should be selected? | The DSS shall manage alternative timeline options | Calculate alternative timeline options by incorporating real-time execution progress | If timeline alteration is required, either adding/dropping tasks, changing task time durations or simply a reordering of tasks, the system should be able to manage those alterations and know if they are feasible. Addressing this ambiguity could be cast as a multi-objective optimization problem similar to Felker (2012). However, the application of this problem would be made available during EVA execution, as opposed to only the EVA timeline planning problem. Potential optimization criteria could include timeline margin, number and type of tasks (weighted by priority),geospatial distribution information of personnel and assets as well as historical data from prior timeline execution statistics. The implementation of these options is heavily task dependent and ultimately link to the particular EVA objectives. The challenge here is how can this data be correlated to the tasks being performed and to be performed with respect to the impact of the tasks on the rate of consumption of consumables and system functionality. |
| TTA - 32 | What is the current and potential timeline margins given the current state of the crew/ system state? | The DSS shall integrate LSS limitations to estimate current and potential timeline margin values | Calculate estimated LSS margin values in comparison to potential timeline margin values | Isolating the overall timeline margin variable is critical to making any of this ambiguity more transparent. The extreme maximums must be estimated so a feasible zone of potential solutions can be estimated. The emphasis here is a constraint based approach that makes the limiting variables transparent to provide crew the hard constraints that are relevant to make operational decisions during execution. |
| TTA - 33 | How will the subsequent sequence of tasks influence the timeline task margins? | The DSS shall manage future task sequences in relation to potential timeline margin estimates | Assess future task sequences to identify alterations to the timeline, if required | Once the absolute constraints are know (or estimated), potential future alterations can assessed and updated based on the moment-by-moment execution. This notion incorporates into 'what-if' analysis of tasks to be accoplished for future alterations and how those decisions impact overall constraints and vice cersa. This requirement is really meant to address forecasted alterations to see the implications with regard to timeline margin. Challenges here can include geospatial distributions of personnel and assets and hardware accessibility. Anticipation of future task implications is also highly task dependent. |
| TTA - 34 | How efficiently will the crew perform the subsequent tasks? | The DSS shall estimate future timeline execution progress (based on as-performed data) | Calculate task execution performance based on historical trends to predict future execution performance | What does it mean for an EVA task to be efficient? Some work has tried to quantify this metric but much more work is needed (Looper & Ney, 2005; 2006; 2007). For instance the DSS will need to have historical record of all previous tasks as-performed data for comparison to what is happening in the current timeline. A much more rigorous and robust categorization scheme to define the tasks being performed will be needed. Currently, EVA timelines are custom built and, for the most part, are unique making one-to-one comparisons difficult. If we can come to agreement on a classification scheme that is consistent and flexible to changes or additions, we can begin to make progress towards defining EVA 'efficiency.' Additionally, the current culture surrounding astronaut performance is rooted in anonymity which will likely be challenged as future systems attempt to make these metrics more explict. |
| TTA - 35 | Were the completed tasks successfully performed? | The DSS shall track the verification and validation of task completion | Track and catalog task execution progress and compare that to presupposed success criteria | This requirement links back to the issue: what is the minimum success criteria for task completion? The DSS should know that information and track the verification and validation of task completion. Currently, verbal/visual confirmation from the EV crew is utilized to confirm a task has been performed to exact specifications. Utilize alternate modes of V&V do exist. For engineered systems, signals can be sent from the hardware to the system to confirm completion. Video data can be used to passively confirm tasks confirmed based on visual cues and signals. Natural language from the crew could be processed so that a digital system can understand what task was just completed. The main source of ambiguity here is that the crew are the primary data source for knowing tasks are completed to specification and for the most part the success criteria is well defined. What happens when objectives will more ill-defined success criteria are performed (e.g. scientific exploration tasks)? |
| TTA - 36 | Should (can) assets be redistributed to support task execution? | The DSS shall manage timeline assets temporally and geospatially to ensure adequate support for crew to complete tasks | Track the location and status of assets/tools to ensure availability and readiness for task execution | Ideally, the system should be predictive in what will be needed in timeline execution and help with the distribution/ redistribution of assets to satisfy that anticipation. This requires the system to know where all relevant assets are geospatially but also how they are distributed in relation to the temporal execution of the timeline. Availability and readiness will be key measures in meeting this requirement because those have direct impact on timeline execution progress. |

Table A.19: Decision ladder results for TTA - Goals stage

## TTA - Goal(s)

| ID | SME State of Knowledge (SoK) | Requirement Intent |
|---|---|---|
| TTA - 37 | Execute all EVA objectives safely and efficiently | The goal for the TTA DL is to ensure the successful execution of all EVA objectives safely and efficiently. Success criteria are assumed to be a priori assigned and designed into the EVA timline. Safety and efficiency are highly multi-dimensional and are also a priori determined. Ideally, the timeline itself has already factored in relevant safety and efficiency measures such that by following the nominal timeline, the crew inherently keep within those definitions. One of the challenges of this goal is the uniqueness associated with each and every EVA timeline execution. The variety of objectives are vast and each present their own unique demands on safety and efficiency. All strategic planning analyses are assumed to occur prior to execution. If provided enough definition upfront, the crew will ideally be expected to perform tactical decisions that impact current EVA timeline objectives and not spend too much time worrying about 'strategic' level objective execution. However, as we aim to perform longer duration missions with many more EVAs throughout those missions, the tactical execution of a single EVA will have mission level implications for subsequent EVAs. |

Table A.20: Decision ladder results for TTA - Ultimate Goals stage

## TTA - Ultimate Goal(s)

| ID | SME State of Knowledge (SoK) | Cognitive Work Requirements (CWR) | Information Relationship Requirement (IRR) | Requirement Intent |
|---|---|---|---|---|
| TTA - 38 | Does the current timeline achieve the desired EVA task priorities? | The DSS shall associate timeline elements to timeline objectives and task priorities | Manage (prioritize) timeline tasks in relation to presupposed timeline objectives | Knowing that current timeline execution progress is actually meeting EVA objectives is paramount to ensuring acceptable objective completion. Furthermore, the system needs to associate those discrete task progress elements with what is actually prioritized. Objectives and prioritizes will be a priori defined and linked to all expected tasks to be performed. In doing so, we offload expectations of the crew to be familiar with the intimate details of why tasks should be completed and emphasize awareness of knowing what is preferred to be completed in the moment. Conveying intent (upfront) will be an important transition to facilitate in time-delayed operations when crew cannot simply ask for an MCC priority without waiting for a response. |
| TTA - 39 | Does the current timeline maintain crew/ vehicle safety? | The DSS shall assess the timeline to assess overall safety of the crew and systems | Compare LSS Margin with Timeline Margin | While simultaneously knowing actual timeline progression, assessments must be made to crew and vehicle safety based on that actual progress. In particular, the DSS must ingest all relevant safety related data to be aware of the health of crew and systems. The foremost measure is awareness of overall timeline margin, which is a fundamental constraint on EVA operations. The life support systems can only support task execution for a finite amount of time. Therefore, all subsequent task/safety related decisions are made under the weight of this variable. The requirement as written related to the LSS and timeline, but can be extended to other factors such as vehicle and other systems that impose similar time limiting constraints that impose a burden on timeline task progress. |
| TTA - 40 | Does the current crew/ hardware functionality enable timeline progress? | The DSS shall manage operational documentation criteria for task execution progression | Integrate documentation (flight rules, inhibits, crib sheets) with system states to maintain safe operational configuration | The EVA community is highly dependent on engineered systems to be successful. As with all engineered systems, engineered and operational constraints exist. Furthermore, flight rules govern the allowable set of actions to be taken, given particular conditions Therefore, the wealth of documented constraints that are associated with these EVA systems will need to be associated to as-performed task progress. Making the crew aware of system functionality to make informed decisions will be important in time-delayed environments, more importantly, knowing the relevant functionality for the current state of operations will be even more operationally useful. This ultimate goal is to make the DSS contextually aware of what the crew are doing and what is actually allowable/doable within the known engineered/operational constraints that are applied to the timeline being executed. |

Table A.21: Decision ladder results for TTA - Goal State stage

## TTA - Goal State

| ID | SME State of Knowledge (SoK) | Cognitive Work Requirements (CWR) | Information Relationship Requirement (IRR) | Requirement Intent |
|---|---|---|---|---|
| TTA - 41 | Should (does) information be relayed to advance the timeline? | The DSS shall manage (transfer) information related to timeline tasks/ hardware | Integrate what information is required to relevant members of the flight team | There is a wealth of details to be managed throughout timeline execution. The exchange of information will be paramount to ensuring adequate task progress. Therefore, the DSS should be able to obtain and potentially exchange pertinent information during execution. The IV operator is envisioned to be the arbiter of this information. Data is not equivalent to information in this context. We need to think through what actual bits of information will be needed during execution and presenting that to the flight team appropriately for real-time execution – The digital timeline resembles the 4-level abstraction already adopted by the EVA operators. With a digital medium, we can include a higher density of information that would otherwise exist in separate entities – e.g. the EVA wiki and the timeline itself are two separate data sources that are manually associated and utilized by EVA flight controllers during execution. Another component to consider here is the mode of communication exchange utilized for information transfer. EVA execution currently leverages audio communication as a prime means of communication. The introduction of new modes of communicaiton represent a large departure from present-day (historical) operations. |
| TTA - 42 | Should the timeline be altered? (adjust the task execution pacing and/or task procedures) | The DSS shall incorporate timeline margin thresholds to manage and assess timeline alterations | Manage the applicability of margin thresholds to timeline execution performance | Timelines will inherently encounter perturbations so the DSS should assist with the alteration of timelines. This alteration process can be thought of in two dimensions: Timelines can be altered in "Time" and "Task." These two perspectives are typically coupled and task dependent. The DSS should be aware of timing thresholds to assist with the alteration process. Alterations should be made only with feasible states. In other words, alterations that are infeasible should be caught within the system so that the EVA crew are not burdened with the responbilities of remembering the minutiae of task and hardware constraints. |
| TTA - 43 | Should system states be altered? | The DSS shall provide the capability for systems to be be altered in relation to the timeline tasks | Manage the reconfigurability of systems to meet real-time execution deviaitions | Just as the timeline may need altered, the EVA systems themselves may need attention. This capability will require the systems themselves to convey their state status and potential needs. This level of system state information will also then need to be related to TTA-42t convey timeline alteration implications. |
| TTA - 44 | Should resources/assets be redistributed? | The DSS shall manage the distribution of assets throughout the timeline | Measure the geospatial/ temporal access to relocate those assets | The distribution of resources/assets will be a constant constraint on operations. Knowing where everything is now and where everything needs to be should be incorporated into the DSS to facility these EVA elements. Measures of accessibility to these assets should be known to some extent. For instance, if an O2 recharge station is available nearby – assessments of timeline execution progress and estimates on timeline forecasts should factor in these resources. Additionally, this requirement will play into how efficient the crew can execute tasks so that productivity towards timeline objectives is maintained. Again, these considerations will then impact how the timeline is executed and potentially altered. |

Table A.22: Decision ladder results for TTA - Task stage

## TTA - Task

| ID | SME State of Knowledge (SoK) | Cognitive Work Requirements (CWR) | Information Relationship Requirement (IRR) | Requirement Intent |
|---|---|---|---|---|
| TTA - 45 | What information/ resources are needed for the desired task and how do they become accessible? | The DSS shall make accessable the information and resources needed to complete timeline tasks | Manage the organization and accessibility of timeline details | Each task has numerous associated bits of information inherently linked to it. Additionally, engineering and operational data linked to both task procedures and tools are incorporated into timeline tasks. There are two components to consider here: what do I need and where do I get it? The “what do I need" component is tied to situation awareness and recognizing that you need something in the first place. The "accessibility" term relates to the ability to obtain what you want (assuming you know what you want), when you want it.The challenge here is the variety and volume of content that could be potentially requested. This ranges from flight rule specifications, engineering data, or any number of other systems/tasks related data and metadata associated with the timeline. |
| TTA - 46 | What procedure needs are present and how are they obtained? | The DSS shall manage the details and interdependancies of tasks procedures and make them accessable for execution | Calculate compatabilities and incompatabilities within tasks and between tasks | At a more granular level, tasks typically have a series of procedure specifications that need to be met in order to successfully complete the task. Each individual procedure assumes a certain state of the environment in order to be ‘allowable’ to be performed. The aim of this requirement set is to formalize the metadata associated with these procedures so that interdependencies is more transparent. The ‘break-out’ and ‘break-in’ of tasks causes states of systems and environments to potentially slip from operational acceptability. The DSS should be able to track and recognize procedure incompatibilities. Metadata such as "order of operations" is one example of procedure support. But what does order of operations mean when you stop part-way thru a procedure and then want to resume the procedure at a later point in the timeline? How does that time in-between impact the remaining procedures to be completed? Knowing where these points are in the interdependencies between tasks/procedures will also be important when you start restructuring the tasks to accommodate deviations and delays. |
| TTA - 47 | What needs to be performed to advance timeline progress? | The DSS shall incorporate baseline success criteria required to advance the tasks within a timeline | Manage baseline success critieria in relation to tasks as executed | Success is measured in the completion of tasks that step towards objective completion. A more explicit measure of success must be managed so that the crew can operate much like they operate now: The crew work locally within the timeline at the task and procedure level; But what about the linkages of local tasks/procedures being performed now with how they impact of subsequent tasks hours ahead in the schedule. Decision points and bingo points can play a role in successful execution management where assessments can be made. Perhaps setting decision points ahead of time could help both crew and MCC have the opportunity to progress the timeline together, each entity granting access to the next stage of the timeline. Again, success criteria exist on numerous levels of timeline abstraction and adhering to those various scales should be considered during execution. |
| TTA - 48 | What environmental and operational hazards/cautions must be considered? | The DSS shall incorporate environmental implications during timeline execution and forecasting | Manage the implications of environmental constraints on current and future task execution | Awareness of environmental and operational hazards play a key role in safety assessments. Crew can have a limited vantage point to see their surroundings and their proximity to regional hazards or targets of interest. System states and configurations that trigger hazards should be integrated into a DSS so that the crew can be aware of those constraints that could potentially impact crew task progress or safety. Could have implications for planetary protection and science progress (e.g. keep out zones) |
| TTA - 49 | What timeline restructuring must take place and what is the resultant timeline? | The DSS shall enable and assist in the restructuring of timelines | Manage the alternatives and implications of structural changes made to timeline components related to planned timeline designs | Timeline restructuring is inevitable. These changes can occur on a task basis and/or temporal basis, and can include but is not limited to removing/adding a task, changing order of operations, or modifying durations of task execution. The DSS should facilitate the restructuring process to maintain feasible timeline solutions. Alternatives management will also likely be a key feature to promote option selection from the crew. Instead of the crew needing to devote cognitive resources to “coming up” with a new plan on their own, they could option select based on their preferences, knowing that the system has also factored in MCC preferences (as much as possible leading up to the decision point.) |

Table A.23: Decision ladder results for TTA - Procedure stage

## TTA - Procedure

| ID | SME State of Knowledge (SoK) | Cognitive Work Requirements (CWR) | Information Relationship Requirement (IRR) | Requirement Intent |
|---|---|---|---|---|
| TTA - 50 | What set of procedures should be used to advance the timeline progress? | The DSS shall allocate the relevant procedures to support task execution | Mange procedures by linking procedures (and crib sheet steps) to tasks | At this stage of the DL, the exact specification or method of implementation becomes hypothetical. The intent at this stage is to consider the ramifications of the specific work practices we envision with the future crew/system team. The act of actually carrying out these procedures will be an evolving hypothesis about what is considered a reasonable work environment. Only by systematically prototyping and testing future systems within an envisioned context can this stage of the DL be realized. |
| TTA - 51 | How should those procedures be integrated into the current timeline? | The DSS shall integrate procedures (both original and modified) during timeline execution | Associate task constraints betweeen sets of procedures (tasks) | |
| TTA - 52 | What information/ resource exchanges are needed to progress within the selected timeline? | The DSS shall facilitate the communication of information/resource needs to support timeline execution | Manage the association of resources to procedures (tasks) | |
| TTA - 53 | What additional information sources are required for timeline progress? | The DSS shall identify context relevant information required to advance the timeline | Manage Task specific content | |

## A.3 Incorporating Research Rigor into this Study

The methodologies implemented throughout the first two phases of CWA warrant a brief review of the steps taken to ensure research rigor. Table A.24 shows the research rigor criteria and the corresponding strategies implemented to satisfy each criteria (see Devers (1999) for a review of research rigor criteria). Integral to this process was the involvement of subject-matter experts in both the development and validation of the resultant CWA models. By leveraging existing CWA model development resources, steps could be taken to ensure credibility, reliability, and objectivity throughout this phase of the thesis.

Table A.24: Description of the strategies implemented to ensure research rigor.

| Criteria | Strategies Implemented |
|---|---|
| Credibility/ Internal Validity | Triangulation was implemented by incorporating a multitude of difference data sources which was guided by established model development protocols as discussed in Section A.1.4 and 3.2.1. |
| | SME review played an integral role in model development process as shown in both Table 3.2 and 3.4. |
| Transferability/ External Validity | Obtaining a detailed description of the work domain context aligned well with the intent of the Cognitive Work Analysis framework. Given the established intent and model artifacts from CWA, the insights derived from this work is readily transferable to a broader audience for consumption. |
| Dependability/ Reliability | The structure of the CWA models provided a natural data archiving mechanism that explicitly links interview insight/material to the resulting research conclusions. |
| | Established interview guides were utilized in each SME interview to elicit domain sight for AH and ConTA model development as discussed in Sections A.1.4 and A.2. |
| Confirmability/ Objectivity | SME input played an important role in validating final models. |
| | Additionally, supplemental discussion points not directly incorporated into the derived requirement statements were gathered and synthesized in brief intent statements to provide supplemental context and explain the overall intent of the requirement statements. |

## A.4 DSS Code and Architecture Development

This section details the specific software code and architectures used to construct the DSS prototypes. First, a brief discussion on using Marvin is provided, and then a more detailed discussion of the internal timeline traits and logic are provided. Finally, the software architectures of the two DSS prototypes are described.

### A.4.1 Brief Description on Using Marvin

The design philosophy behind the user experience (UX) of Marvins timeline view was to keep it as simple as possible. Every extra click takes time away from the IV operator's other responsibilities and introduces the potential for user error. This design philosophy led to the following decisions and guided Marvins UX and behavior.


Figure A.8: Decision ladder results for LSS - Alert stage

As the mission progresses, the IV operator is solely responsible for checking off timeline Steps as they confirm that they have been completed as shown in Figure A.8. If every moment of an EVA timeline is contained within a timeline, we can assume that every Step begins the instant the preceding Step is complete. This arrangement does not allow for gaps of time within the timeline. Under this perspective, "Start" and "stop" buttons were viewed to lead to erroneous downtime between Steps as a result of the non-negligible time between clicking "stop" and "start" buttons. A single start/stop button was used to launch the internal counter that initiated the first Step in Marvin's timeline. The IV operator then checks off the first Step when it is confirmed complete and Marvin immediately starts the clock for the next Step. This process repeats for all subsequent steps.

Marvin takes a conservative approach to timeline calculations. Each Step has a planned duration, that is to say a definite amount of time (internally measured in seconds) with a definite start and end PET within the overall EVA, which should have a planned PET equal to the sum of all Step planned durations. A Step is assumed to be progressing nominally while its elapsed duration is less than its planned duration. If the elapsed duration exceeds the planned duration, the difference is reflected in the timeline calculations.

Upon receiving a signal that a Step was checked off, Marvin stops increasing the elapsed time for the checked off Step and begins increasing the elapsed time for the next Step. As such, the "resolution" of Marvin's reported timeline statistics is only as detailed as the resolution of the timeline itself. It essentially can only be assumed to be perfectly accurate the instant an element has been checked off. If a larger duration Step does not contain sub-Steps, Marvin's accuracy may drift from actual performance because periods between known steps evolve in time linearly. For instance, if the elapsed duration of a translation Step is less than the planned duration, Marvin will report the mission is nominal until the translation Step is checked off, thereby updating the relevant metrics. However, if the translation Step had sub-Step components with specified durations, Marvin can take into account the sub-Step progress and report accurate timeline statistics throughout the translation Step execution.

### A.4.2 Marvin Timeline Details

The EVA timeline structure was generalized to a hierarchical data structure, often called a "tree." Marvin needs to represent sequenced, multi-level actions within actions. As such, Marvin's timeline tree consists of an ordered and four level deep nested series of EVA actions. Based on our designs, every moment of the EVA is represented within one of the four levels of Marvins Timeline. See Chapter 4 for a discussion of Marvin timeline structure.

A single action within a level of the Timeline is called a Step. We defined four hierarchical Steps of a Timeline: Activity, Task, Subtask, Procedure. Activities represent the highest level of the Timeline. They may account for hours of EVA time and identify distinct phases (e.g. translations, station operations, overhead activity, etc.) Each Activity may include zero or more Task children. Tasks describe checkpoints within Activities, usually measured on the order of tens of minutes. For instance, a station operation Activity may include Tasks that represent phases of scientific experiments. Within translation activities, Tasks may represent reaching traversal waypoints.

Tasks may include zero or more Subtask children. Subtasks begin to describe minute-by-minute, step-by-step aspects of a timeline. For instance, the Task of operating a science apparatus may include Subtasks for configuring individual components. Finally, each Subtask may include zero or more procedures, where a Procedure represents a quantum of action by the crew member (e.g. tightening a bolt, turning a lever, actuating a telescopic arm, etc.).

Note that children are always optional. The level of detail included in a Timeline is up to the EVA design team's discretion - Marvin's Timeline calculations work the same regardless, however, the more granular details the Timeline contains, the more accurately Marvin will be able to report timeline progress. Each Step must include a short description and may optionally include a planned duration (in seconds), or PET required to complete the Step. Marvin also tracks every crew member individually, and as such each step must also identify the crew member responsible for it (with each crew member's data occupying a channel).

Note that while channel can be set arbitrarily against any Step, in practice, the channel of a Step is determined by its parent Activity. We set channels against Activities, which get propagated down the Timeline to deep[2] children.

[2]"Deep" in this context refers to all children of children of children, etc, from a parent down to the bottom of the tree (explicitly - down to children elements that do not have children).

Furthermore, every Step has a unique ID within the timeline, which simplifies the process of identifying Steps during timeline calculations.

There are five possible states for any Step, all of which are determined on the fly every second during EVA progress:

- Fresh: incomplete and has never run.
- Active: is currently running and is not complete.
- Complete: has run and has been completed.
- Paused: has run and has been stopped without being completed.
- Skipped: has never run but is marked complete. Marvin treats this situation the same as a complete step.

### A.4.3 Ephemeral Timing Data

Marvin differentiates Timeline descriptions, which may be shared across EVAs, from timing data collected during a mission. Marvin takes the view that timing data reflect the execution status of a single EVA. It follows that Marvin must also differentiate planned and elapsed durations. While planned durations are metadata that may be shared across missions, Marvin calculates elapsed durations on the fly during EVA execution.

Marvin tracks three separate time-related values for every step:

- **Planned durations**, which may be set explicitly in Timeline metadata or determined implicitly.
- **Elapsed durations**, which are calculated as either $PET_{end} - PET_{start}$ or $PET_{now} - PET_{start}$ depending on the Step's state of completion.
- **Projected durations** which only apply to active steps. This projection estimates the time to complete an active step based on how much time has elapsed and how much time was planned. This calculation provides the most insight when applied against parents with many children, or the Timeline as a whole, because timing calculations against high level Steps are effectively aggregates of the time calculations against its lower level children.

Trees are inherently nonlinear, which poses a problem for calculations against time, which flows linearly. Calculating time values for a parent with children necessitates knowledge of the state of all of its children. Timeline progress metrics similarly suffer. Deciding if a parent is active requires knowledge of the state of every deep child (every generation of children to the bottom of the tree) such that $Parent_{isactive} = child_{1isactive} \vee child_{2isactive} \vee ...child_{nisactive}$. If any child Step is active within a parent, Marvin treats the parent as active as well.

Two potential solutions were examined to simplify the hierarchical timeline math. In the first solution, the timeline was flattened into a linear path based on Kahn's Algorithm for topological sorting[3], and in the second the bottom layer of the Timeline was directly pruned.

While it may be mathematically possible to work with Kahn's Algorithm, we found that it translated the same hierarchical issues to a linear model without simplifying calculations or simplifying Marvin's software architecture (making the math, in fact, more difficult to reason about). We decided to prune the bottom layer of the Timeline into a Linear Timeline made of Ministeps ("mini" in the sense that they include some of but not all of the information contained within Steps in the Timeline). We used a transformation with the following rules and postulates:

- Planned EVA duration = sum from 0 to total ministep count [ministep duration n]
- Simple: Parent duration = D; Child duration = D / number of children under parent
- Accurate: Child duration = (D - allocated time) / number of non manually set children under parent
- LT = list in order of ministep without children

**P1** Every instant of the EVA must be represented in the Timeline.

**P2** Time waterfalls from parents to children evenly to the lowest level of the tree, such that the sum of the times (planned or elapsed) of a parent's children equals the time of the parent.

- A child may have a manually set planned duration, in which case time flows from the parent to the child's siblings evenly.

**P3** Only the lowest children in the tree may be used for time calculations.

[3] https://en.wikipedia.org/wiki/Topological_sorting

Postulate 1 (P1) clarifies that upon completing one step, the next step begins without downtime. Postulate 2 (P2) dictates that every parent distribute its planned time to its children. If those children have children, they redistribute their time to the next generation down. As such, every planned moment of the timeline evenly sinks to the bottom of the tree. Postulate 3 (P3) culls the lowest level of the tree (where the lowest level is a step without children, regardless of the type of step) and places these steps in a separate Linear Timeline that represents every moment of the mission in chronological sequence. Marvin tracks the connection between Timeline and Linear Timeline, such that it can identify which steps in the Linear Timeline correspond to a step at any level in the Timeline.

### A.4.4 Timeline Calculations

To perform time calculations against a parent, Marvin identifies its deep children in the Linear Timeline by traversing from the original parent in the Timeline down through deep children until it finds Steps that do not have children. Marvin captures the IDs of the Steps that were found, which can then be located within the Linear Timeline.

The following general formulas apply to both individual Steps and the whole Timeline. Note that Marvin does not make a distinction between calculations running against a single Step and the entire Timeline. Calculations against the Timeline are, in effect, calculations against a parent Step with every other Step as a deep child, making every Ministep in the Linear Timeline a child.

It is worth noting that Marvin creates a Linear Timeline for each channel of the Timeline (e.g. every EVA crew Timeline is linearized independently). Though there is usually strong correlation between EV crew Timelines and their execution objectives, Marvin takes a naïve stance and assume independent execution. As such, many overall timeline calculations (especially any involving PET) involve performing the same calculations against Linear Timelines from both channels and then returning the most conservative result. For instance, if PET Remaining for channel 1 is 01:50 while channel 2 is 01:55, the overall

PET Remaining reported is the greater of the two, 01:55.

The following calculations are made throughout EVA execution to populate the Marvin header for IV consumption. Marvin runs a loop where it performs timeline calculations once every second.

- **Planned Duration**: Sum planned duration fro each ministep from 0 to total ministeps [planned duration n]
- **PET Remaining**: (remaining time for running ministeps) + (planned time for fresh ministeps) + (projected time remaining for paused ministeps)
- **Projected Duration**: (duration of completed ministeps) + (planned duration of fresh ministeps) + (planned duration OR elapsed duration, whichever is larger, for active ministeps and paused steps)
- **Projected Duration**: Note that project durations will grow as actual step durations exceed planned durations.
- **Is a Step Active?**: $Step_{isactive} = child_{1isactive} \vee child_{2isactive} \vee ...child_{nisactive}$
- **Time Behind**:(Planned EVA Duration) - (Projected EVA Duration); Note that Time Behind is only ever used in the context of the entire Timeline.
- **Timeline Margin**: (PET Remaining for channel) - (Limiting Consumable remaining for channel); Note that with the current iteration of Marvin, Timeline Margin represents the one and only metric on the timeline view that integrates telemetry. Once again, the same calculation is performed against each channel with the most conservative value returned.
- **Time Until Start**: (sum of PET remaining for incomplete, e.g. active, fresh, or paused, preceding ministeps); Note that for each Activity, this variable calculates the projected time to complete all preceding Activities, which provides an estimate of when that Activity should start.

### A.4.5 Marvin Software Architecture

Marvin is built as a web-based tool that consists of three main components - the front end application (i.e. the thing that you see and click), the loop and the database. Three languages were used: HTML (HyperText Markup Language), CSS (Cascading Stylesheets) and JavaScript. HTML describes the structure and content of a website and CSS describes the style of a website. JavaScript can change the structure, content and style on the fly. Of the three languages, only JavaScript is a full-blown programming language. HTML and CSS are markup languages, much like LaTeX, in that they describe documents but are not Turing complete.

A front-end framework is responsible for stamping that user data into pre-defined templates. Marvin uses a front-end framework called Polymer[4] to inject EVA specific data into the custom templates we designed. The front end code, consisting of HTML, CSS and JavaScript files, is rendered by Electron into the website that users can see and click. The front-end app exists in two contexts (and is effectively identical in each) - the Marvin desktop application loads the files and displays them as the application interface through a web browser, e.g. Google Chrome, and Marvin contains a server that is capable of sending (nearly) the same files to any web browser on the same network as the machine running Marvin. This allows the administrator running Marvin and any user to see the same interface.

Marvin relies on a database to store and share mission information. In this context, "database" specifically refers to software that is capable of storing arbitrary data, executing search queries against the data, and sharing the data to clients over a network. Effectively every website and application uses a database to store data. We chose database software called PouchDB[5] to store data within Marvin. Marvin runs a PouchDB server inside the application. Its data is accessible to Marvin's front end and the web browser front end. This configuration depicts the Advanced DSS only. The Baseline DSS utilized a simplified scheme, as shown in Figure A.9.

Specifically, the database consists of a few namespaces best described as separate regions of storage. Organizing a database with namespaces is akin to organizing a large directory of documents into structured subdirectories. Marvin contains namespaces for the timeline itself, the ephemeral timing data and the telemetry data.

With PouchDB, clients receive data directly from databases, which may or may not be

[4] https://www.polymer-project.org/
[5] https://pouchdb.com/

a good thing. In general, it's a bad idea to allow clients direct access to a database because unfettered access to a database means that clients may be able to create, update and delete data in ways you, the owner of the db, may not want. However, it also takes work to expose data from a db to clients through another application, often called an API. APIs require time and effort to build and we wanted a prototype quickly. PouchDB was chosen because it allows clients to listen for changes to a database and receive new data the instant it is updated, which means it basically acts as its own API. As such,the clients listen to the databases and then update their views with new data as it arrives. In effect, updating the database simultaneously broadcasts data to all of the clients.

Lastly, Marvin runs a loop to periodically update calculations and then broadcast fresh data to front end clients as an EVA progresses. There are two subcomponents within the loop - one calculates instantaneous telemetry values, while the other merges the timeline and ephemeral timing data into a larger structure to be broadcasted. Upon receiving new data, the front-end application update their displays. The front-end applications also listen for changes to the telemetry database, which runs on a separate 20 second loop. Front-end applications pick up the new value by listening for changes to the telemetry database and then updating the telemetry view with the new data.

*Baseline DSS Architecture*

The Baseline DSS architecture schematic is shown in Figure A.9 .The Baseline DSS uses a linear data flow designed to mimic real data recorders. The Hardware layer acts like a data receiver, except rather than recording analog sensor signals, it parses and stores simulated telemetry from a CSV file. The Sensors layer receives "raw" hardware signals and separates and organizes the information into distinct channels for each sensor. The Sensors layer publishes the parsed telemetry to a Redis[6] database running in publish/subscribe mode, which stores the telemetry and notifies the final layer, a Client server, that new data is

[6] https://redis.io/

ready. The Client layer takes the responsibility of disseminating telemetry to web browsers in a data format that browsers can easily receive, parse and display.

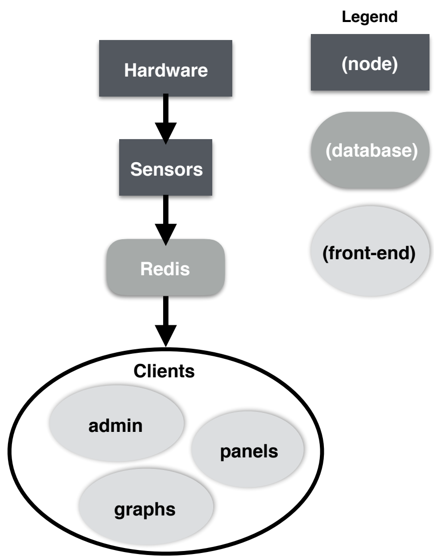


Figure A.9: Baseline DSS architecture schematic.

*Advanced DSS Architecture*

The Advanced DSS (Marvin) architecture schematic is shown in Figure A.10. The first iteration of the Marvin timeline view was built to be as portable as possible. While most server software requires some amount of non-trivial installation and configuration, desktop applications do not. As such, we built Marvin as a desktop application using the Electron framework, which packages a website into a standalone application.

### A.4.6 Hardware Considerations

Both the Baseline and Advanced DSS were developed and run on Unix machines and the front end views work in both Google Chrome and Firefox web browsers. The human subject study was conducted by hosting the DSS software on a Mac Book Pro with the follow specifications: 2.5 GHz Intel Core i5 and 8 GB 1600 MHz DDR3. A wireless network connection linked the host machine with the IV workstation which was using

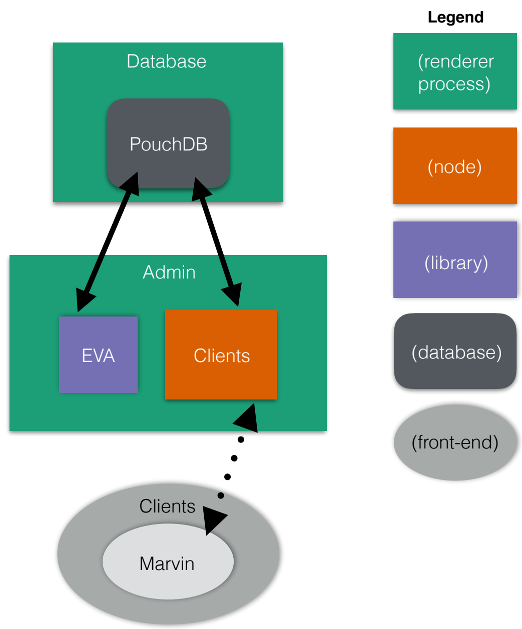


Figure A.10: Advanced DSS (Marvin) architecture schematic.

Windows 8.1 with an Intel(R) Core(TM) i7-4700MQ CPU running at 2.40 GHz with 24 GB of RAM. A NVIDIA GeForce GTX 770M graphics card powered two 1680x1050 (32 bit) resolution wide screen monitors at 60 Hz refresh rate.

## A.5 GT DSS Human-in-the-Loop Experiment Materials

### A.5.1 Informed Consent

### A.5.2 EV and IV - Nominal Timeline Examples

### A.5.3 Biographical Questionnaire

### A.5.4 Intravehicular Operator Proficiency Assessment

### A.5.5 NASA Taskload Index (TLX) Questionnaire

### A.5.6 Cognitive Support Assessment Questionnaire

### A.5.7 Interaction Assessment Questionnaire

**School of Aerospace Engineering**
**Cognitive Engineering Center**
**Georgia Institute of Technology**
**Human Subject Consent**

1. **Project Title**: Decision Support System Development for Human Extravehicular Activity

2. **Principal Investigator**: Dr. Karen Feigh, 404-385-7686, karen.feigh@gatech.edu

   **Graduate Students**: (Lead) Matthew Miller, 912-674-6722, mmiller@gatech.edu
   Rachel Haga; Marc Canellas; Lanssie Ma

   **Undergraduate Students:** Austin Claybrook; Suraj Greenlund; Shaheer Sajid; Ebrahim Yavari; Kristina Bates; Connor Hutcheson; Caroline Jones; Matthew Gilmartin

3. **Protocol and Consent Title:** Decision Support System Development for Human Extravehicular Activity

4. **Introduction**: You are being asked to be a volunteer in a research study. We are seeking your participation in a human in the loop simulation study to evaluate a set of computer support systems for future astronauts to use during missions outside of the spacecraft or habitat. You will be asked to complete a series of test scenarios and surveys to help the researchers better understand your experiences as a participant in the simulation to inform the design of future computer support systems.

5. **Purpose:** The purpose of this study is to study the work environment astronauts will face in future human spaceflight missions while conducting human missions outside of the spacecraft or habitat.

6. **Exclusion/Inclusion Criteria:** Participants in this study must be enrolled as a graduate student at Georgia Tech and have passed their PhD qualification exams. Those who plan to graduate prior to August 2016 may not be in this study. You must be proficient in English and not have colorblindness.

7. **Procedures**:

   This study has four phases:
   1. Training (4 hours)
   2. Data collection session 1 (4 hours)
   3. Data collection session 2 (4 hours)
   4. Data collection session 3 (4 hours)

   If you decide to be in this study, your participation will involve a minimum of an initial certification session, which will last no more than 4 hours in duration. If you pass the certification session, your involvement will consist of 3 additional data collection sessions.

   In the initial visit, you will conduct a training session to familiarize you with the standard operating procedures and tools you will be required to use in the simulation. Once training is completed, you will complete a certification simulation. The simulation itself includes the use of paper and a computer to complete a procedure-scheduling task. The results from the certification simulation will then dictate whether you will be invited to participate in the remaining data collection sessions. You will be notified within 1 business week after performing the certification simulation of your results. If you do not pass, your participation in the simulation will terminate and you will be compensated $40.00 for your time.

Page 1 of 3

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Figure A.11: Human subject study consent form approved by Georgia Tech Institute Review Board - page 1.

If you pass, the subsequent testing sessions will be scheduled at a later date, which is mutually agreed upon.

The $2^{nd}$ session, lasting no more than 4 hours in duration, will consist of a series of simulations similar to those performed during the first testing session. A set of questionnaires will be completed after each testing condition and again at the end of each testing session.

The $3^{rd}$ testing session, lasting no more than 4 hours in duration, will include supplemental training and practice on an experimental computer support prototype to be used in the subsequent sessions.

The $4^{th}$ testing session, lasting no more than 4 hours, will be similar to the $2^{nd}$ testing session.

The total amount of time you will be in the laboratory is no more than 16 hours, divided into 4 testing sessions. Each session will be scheduled at a mutually agreed upon time and your monetary compensation will be prorated on how many testing sessions you complete. Remember, you may stop at any time.

**Note:** the simulation environment will be recording audio and video of your simulation execution to supplement later data analysis.

8. **Foreseeable Risks or Discomforts**: The probability and magnitude of harm or discomfort anticipated in the proposed research are not greater than those ordinarily encountered in everyday life or during performance of routine computer based office tasks or coursework.

9. **Benefits**: There are no direct benefits to you for participating in this research study. The study will help lay the framework for future studies to enhance human-exploration capabilities in future human spaceflight missions.

10. **Compensation/Costs**: Participants in this study may be compensated up to $200 if they complete all 4 sessions. Participants will be compensated $40 for the initial session, $45 for the $2^{nd}$ session, $55 for the $3^{rd}$ session and $60 for the $4^{th}$ session.

11. **Costs to You:** There are no costs to you, other than your time, for being in this study.

12. **Confidentiality**: Your privacy will be protected to the extent allowed by law. Each participant will be randomly assigned a number, and his or her data will be recorded only in terms of that number. A key linking the number to each participant will be recorded in a password protected file on a password-protected computer during data collection. All electronic data (notes, reports, audio, and video) will be kept in password-protected files on password-protected computers. De-identified information resulting from the testing sessions will be disclosed in technical reports, conference papers, journal papers and academic dissertations and published. All data that are identifiable will be destroyed by secure erasure of digital copies or by shredding of paper- copies prior to the end of the study. To make sure that this research is being carried out in the proper way, the GT Office of Research Integrity Assurance may review study records. The Office of Human Research Protections may also look over study records during required reviews.

13. **In Case of Injury/Harm:** If you are injured as a result of being in this study, please contact Principal Investigator, Karen Feigh Ph.D., at telephone (404) 385-7686. Neither the Principal Investigator nor Georgia Institute of Technology has made provision for payment of costs associated with any injury resulting from participation in this study.

14. **Contact Person**: If you have questions about the research, call or write Dr. Karen Feigh at 404-385-7686, Montgomery Knight Building, Room 419, Georgia Institute of Technology, 270 Ferst Drive, Atlanta GA 30332-0150.

Page **2** of **3**

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Figure A.12: Human subject study consent form approved by Georgia Tech Institute Review Board - page 2.

15. **Voluntary Participation/Withdrawal**: You have the right to withdraw from the study at any time without penalty. The audio recordings along with all questionnaires and transcripts will be destroyed upon your withdrawal from the study.

16. **Participant's Rights:**
    1. Your participation in this study is voluntary. You do not have to be in this study if you don't want to be.
    2. You have the right to change your mind and leave the study at any time without giving any reason and without penalty.
    3. Any new information that may make you change your mind about being in this study will be given to you.
    4. You will be given a copy of this consent form to keep.
    5. You do not waive any of your legal rights by signing this consent form.

17. **Questions about the Study:** If you have any questions about the study, you may contact Dr. Karen Feigh at 404-385-7686, or karen.feigh@gatech.edu, Montgomery Knight Building, Room 419, Georgia Institute of Technology, 270 Ferst Drive, Atlanta GA 30332-0150.

18. **Questions about Your Rights as a Research Participant:** If you have any questions about your rights as a research participant, you may contact:

    Ms. Melanie Clark, Georgia Institute of Technology
    Office of Research Integrity Assurance, at (404) 894-6942.
    OR
    Ms. Kelly Winn, Georgia Institute of Technology
    Office of Research Integrity Assurance, at (404) 385- 2175.

If you sign below, it means that you have read (or have had read to you) the information given in this consent form, and you would like to be a volunteer in this study.

________________________________________
Participant Name (printed)

________________________________________ ____________
Participant Signature Date

________________________________________ ____________
Signature of Person Obtaining Consent Date

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Figure A.13: Human subject study consent form approved by Georgia Tech Institute Review Board - page 3.

## EVA – 6S: STAGE EVA – TRANSLATION TO STATION #4 (00:15)

### IV

1. Record Observational notes *when directed* by EV crew
2. Systems Check **prior** to station arrival

| Variable | EV1 (CDR) | EV2 (MMP) |
|---|---|---|
| O2 | | |
| Pressure | | |
| EMU Faults | | |
| Water | | |

3. Estimate time of arrival
4. Compute estimate of minutes behind (projected minus planned arrival time)
5. Compute estimate of timeline margin
6. How Confident are you in your estimate (+/- min)

### EV1 (CDR)

TRANSLATION (00:15)

1. Correlate observation with active geophysical data
2. Inspect targets of opportunity as appropriate
3. Photograph features while driving if possible
4. Monitor active regolith analysis data as appropriate
5. Correlate active data sources with observations

### EV2 (MMP)

TRANSLATION (00:15)

1. Operate rover along preplanned route

**NOTE**

- In traversing from Station #3 to 4 the surface characteristics should change from the blocky Front material to a smoother mare material. The Traverse will pass along the south western edge of a secondary crater cluster.
- Things to look for during this portion of the traverse are the secondary crater deposits and their relationship to surrounding terrain and eastern edge of the debris flow from the Front.
- Photographic documentation of these features is desirable.

EVA - 6S - TX_S2_Run1 - IV CREW 1

## EVA – 6S: STAGE EVA – STATION #4 ACTIVITIES (00:15)

### IV

1. Record PET at Arrival
2. Convey summary of tasks to be performed by each crew member
3. Record number and type of samples identified for sampling (note any specific details as instructed by MMP)

| Sample ID | Container ID | Sample type (lvl of alt – H/M/L) |
|---|---|---|
| | | |
| | | |
| | | |
| | | |
| | | |

**NOTE**

Check Mission Log for MCC Activation Criteria **PRIOR** to Activation

4. **Confirm GO** for CDR MRU activation once MCC approves

### EV1 (CDR)

GEOPHYSICAL MRU EXPERIMENT (00:15)

1. Egress Rover
2. Unload MRU
3. Select and place MRU at sampling site
4. Configure MRU **C5** (00:03)
   - ❑ Loosen Hypotenuse Slider friction lock
   - ❑ √ Partially collapse boom lifting boom feet off the surface
   - ❑ Tighten Hypotenuse Slider friction lock
   - ❑ Check that boom feet are clear of ground obstacles in the intended sweep path
   - ❑ Release yaw line from fairlead carabineer
   - ❑ √ Translate to Yaw Joint base and retrieve yaw line
   - ❑ Translate to Yaw Joint PIP pin with yaw line in tow
   - ❑ Check hardware clear of intended motion path and moving joints
   - ❑ √ Check Yaw PIP pin (1) retracted
5. Activate MRU **C5** (00:02)
   - ❑ Retrieve Anchor by opening lid of MRU
   - ❑ Connect Powered Driver to Anchor End Effector, check that both latches engaged
   - ❑ √ Anchor GeoArray to the surface by driving Anchor End Effector through Anchor Hole
   - ❑ Disconnect Power Driver from Anchor End Effector by simultaneously depressing both side latches
   - ❑ √ Connect Powered Driver to a Seismic Sensor End Effector check that both latches engaged
   - ❑ √ Check for confirmation to activate MRU

### EV2 (MMP)

GEOPHYSICAL SAMPLING (00:15)

1. Park and Egress rover
2. Unload Sampling MRU and camera
3. Make Observations while photo documenting (00:03)
   - ❑ Report site context description
   - ❑ Environmental conditions (depth, current strength/direction, temperature, visibility)
   - ❑ Unit descriptions (distinguishing features, unit relations and orientations)
   - ❑ Variances from precursor data
   - ❑ Other notable features
4. Worksite Setup / Sample Prep (00:02)
   - ❑ Set sampling markers next to candidate samples
   - ❑ √ Each candidate samples are photographed
5. Collect Samples (00:02)
   - ❑ Connect Manual Driver to Rock End Effector, pushing until Latch clicks into place
   - ❑ Remove Manual driver and effector from Sampling MRU
   - ❑ Squeeze and hold handle of Manual Driver while placing over sample of interest
   - ❑ Release handle, capturing sample inside End Effector
   - ❑ √ Stow End Effector in Sample MRU
6. Repeat Sampling procedures until desired samples are collected

**CAUTION**

- Avoid touching End Effectors to minimize contamination
- Latch may over extend when clicking into place

EVA - 6S - TX_S2_Run1 - IV CREW 2

Figure A.14: IV detailed timeline for nominal scenario condition - page 1 and 2.

## EVA – 6S: STAGE EVA – STATION #4 ACTIVITIES (00:15) CONT.

### IV

5. Confirm MRU system checkout complete
6. Confirm each sample is collected and stowed
7. Provide MCC with a quick verbal status update of activities performed at Station #4.
8. Compute estimate of minutes behind (projected minus planned end time of Station #4 activities)
9. Do you think the EV crew will finish Station #4 on time? If not, what is your estimated end time?

   **Y / N** | Estimated end time:

10. Systems Check **prior** to station departure

| Variable | EV1 (CDR) | EV2 (MMP) |
|---|---|---|
| O2 | | |
| Pressure | | |
| EMU Faults | | |
| Water | | |

**NOTE**
Check Mission Log for MCC Translation GO Criteria **PRIOR** to Translation

11. Record PET at Departure

### EV1 (CDR)

GEOPHYSICAL MRU EXPERIMENT (00:15)

6. Perform system checkout
   - ❑ √ System state variables
   - ❑ Confirm System Checkout
7. Clean-Up Worksite
   - ❑ √ MRU Systems on data collection standby mode
   - ❑ √ All panels of MRU are secure and closed
   - ❑ Stow hardware tools in MRU containment bag
8. Stow Hardware
   - ❑ √ All tools stowed and secured in containment bag
   - ❑ Stow containment bag on Rover
   - ❑ √ Tether straps secure on all compartments on Rover
9. Mount rover (Fasten Seatbelt)
10. Verify rover scientific instruments active
11. Verify following in good config prior to commencing translation (00:02)
    - ❑ Seat belts fastened
    - ❑ Cooling
    - ❑ Visors
    - ❑ Glove heaters
    - ❑ √Tools & Tethers clear
    - ❑ √Gloves & HAP system
12. Confirm GO for Translate

### EV2 (MMP)

GEOPHYSICAL SAMPLING (00:15)

7. Verify ALL sample IDs with sample container IDs
8. Clean-Up Worksite
   - ❑ √ All panels of MRU are secure and closed
   - ❑ Stow hardware tools in MRU containment bag
9. Stow Hardware
   - ❑ √ All tools stowed and secured in containment bag
   - ❑ Stow containment bag on Rover
   - ❑ √ Tether straps secure on all compartments on Rover
10. Mount rover (Fasten Seatbelt)
11. Verify following in good config. prior to commencing translation (00:02)
    - ❑ Seat belts fastened
    - ❑ Cooling
    - ❑ Visors
    - ❑ Glove heaters
    - ❑ √Tools & Tethers clear
    - ❑ √Gloves & HAP system
12. Active rover from sleep mode
    - ❑ Verify NAV states
    - ❑ NAV RESET "RESET" - "OFF"
    - ❑ Position LGA 020$^0$ at Power Up
13. Confirm GO for Translate

EVA - 6S - TX_S2_Run1 - IV CREW 3

## EVA – 6S: STAGE EVA – TRANSLATION TO STATION #5 (00:05)

### IV

1. Record Observational notes *when directed* by EV crew

**NOTE**
If crew Egress to photograph sample(s) during transit. PERFORM an abbreviated systems check **prior to Ingress:**
- ❑ √Tools & Tethers clear
- ❑ √Gloves & HAP
- ❑ √Seat belts fastened
- ❑ √Nav System Engaged

2. Estimate time of arrival
3. Compute estimate of minutes behind (projected minus planned arrival time)
4. Compute estimate of timeline margin
5. How Confident are you in your estimate (+/- min)

### EV1 (CDR)

TRANSLATION (00:05)

1. Correlate observation with active geophysical data
2. Inspect targets of opportunity as appropriate
3. Photograph and describe sample features
4. Monitor active regolith analysis data as appropriate
5. Correlate active data sources with observations

### EV2 (MMP)

TRANSLATION (00:05)

1. Operate rover along preplanned route

**NOTE**
- In traversing from Station #4 to 5 the surface characteristics should change from the fine grained sand to a smoother mare material.
- Things to look for during this portion of the traverse are transition zones between sandy and mare material and their relationship to surrounding terrain and eastern edge of the debris flow.
- Photographic documentation of these features is desirable.

EVA - 6S - TX_S2_Run1 - IV CREW 4

Figure A.15: IV detailed timeline for nominal scenario condition - page 3 and 4.

## EVA – 6S: STAGE EVA – STATION #5 ACTIVITIES (00:35)

### IV

1. Record PET at Arrival

2. Convey summary of tasks to be performed by each crew member

3. Confirm correct MRU ID

4. Record number and type of samples identified for **Rock** sampling

| Sample ID | Container ID | Sample type (lvl of alt – H/M/L) |
|---|---|---|
| | | |
| | | |
| | | |
| | | |
| | | |

**NOTE**
Check Mission Log for MCC Activation Criteria **PRIOR** to Activation

5. Confirm GO for CDR MRU activation

### EV1 (CDR)

GEOPHYSICAL MRU EXPERIMENTS (00:35)

1. Egress Rover

2. Unload MRU **B7**
3. Search and Select MRU at sampling site
4. Confirm once MRU at sampling site

5. Configure MRU **B7** (00:02)
   - ❑ Release the 4 sensor to make contact with surface
   - ❑ Engage deployment packet and relocate **B7** components southwest of anchor point
   - ❑ √ Pull socket pin
   - ❑ Rotate package
   - ❑ remove dust cover
   - ❑ deploy anchor legs
   - ❑ √ Place secondary probes on surface
   - ❑ Level and align antenna

**WARNING**
- Avoid touching the upper half of the Antenna during installation so as to not damage gloves from hot surface

6. Activate MRU **B7** (00:02)
   - ❑ Place pkgs on surface with expts pkg in final position
   - ❑ Disconnect pwr pkg from bar
   - ❑ Reposition pwr pkg 10 ft East Remove HFE stowage pip pins
   - ❑ Tip power package down
   - ❑ Release RTG cable B. bolts
   - ❑ Deploy RTG cable & discard cable reel
   - ❑ √ Check for confirmation to activate MRU

### EV2 (MMP)

GEOPHYSICAL SAMPLING (00:35)

1. Park and Egress rover

2. Unload Sampling MRU, camera and make Observations while photo documenting the site (00:02)
   - ❑ Report site context description
   - ❑ Environmental conditions (depth, current strength/direction, temperature, visibility)
   - ❑ Unit descriptions (distinguishing features, unit relations and orientations)
   - ❑ Variances from precursor data
   - ❑ Other notable features
3. Worksite Setup / Sample Prep (00:02)
   - ❑ Set sampling markers next to candidate samples
   - ❑ √ candidate samples are photographed
4. Collect Rock Samples (00:05)
   - ❑ Connect Manual Driver to Rock End Effector, pushing until Latch clicks into place
   - ❑ Remove Manual driver and effector from Sampling MRU
   - ❑ Squeeze and hold handle of Manual Driver while placing over sample of interest
   - ❑ Release handle, capturing sample inside End Effector
   - ❑ Stow End Effector in Sample MRU
5. Repeat Sampling procedures until desired samples are collected

**CAUTION**
- Avoid touching End Effectors to minimize contamination
- Trigger may kick back when attempting to engage



## EVA – 6S: STAGE EVA – STATION #5 ACTIVITIES (00:35) CONT.

### IV

6. Confirm MRU system checkout complete

7. Confirm each sample is collected and stowed

8. Record number and type of samples identified for **SOIL** sampling

| Sample ID | Container ID | Sample type (lvl of alt – H/M/L) |
|---|---|---|
| | | |
| | | |
| | | |

9. Provide MCC with a quick verbal status update of activities performed at Station #4.
10. Compute estimate of minutes behind (projected minus planned end time of Station #5 activities)

11. Do you think the EV crew will finish Station #5 on time? If not, what is your estimated end time?

**Y / N** | Estimated end time:

**NOTE**
Check Mission Log for MCC Activation Criteria **PRIOR** to Activation

12. Confirm GO for CDR MRU activation

13. Confirm MRU system checkout complete

### EV1 (CDR)

GEOPHYSICAL MRU EXPERIMENTS (00:35)

7. Perform system checkout
   - ❑ √ System state variables
   - ❑ Confirm System Check

8. Unload MRU **A6** (00:02)

9. Select and place MRU **A6** at sampling site
10. Confirm MRU A6 secured at site

11. Configure MRU **A6** (00:02)
    - ❑ Release the 4 sensor to make contact with surface
    - ❑ Engage deployment packet and relocate **A6** SW
    - ❑ Pull socket pin
    - ❑ Rotate package
    - ❑ √ remove dust cover
    - ❑ deploy anchor legs
    - ❑ Place secondary probes on surface
    - ❑ √ Level and align antenna

12. Activate MRU **A6** (00:02)
    - ❑ Place pkgs on surface with exp pkg in final position
    - ❑ √ Disconnect pwr pkg from bar
    - ❑ Reposition pwr pkg and Remove HFE stowage pip pins
    - ❑ √ Tip pwr pkg down
    - ❑ Release RTG cable B. bolts
    - ❑ Deploy RTG cable & discard cable reel
    - ❑ √ Check for confirmation to activate MRU

13. Perform system checkout
    - ❑ √ System state variables
    - ❑ Confirm System Check

### EV2 (MMP)

GEOPHYSICAL SAMPLING (00:35)

6. Verify ALL sample IDs with sample container IDs

7. Collect Soil Samples (00:02)
   - ❑ Remove Manual Driver with Soil End Effector from Sample Briefcase
   - ❑ Squeeze and hold handle of Manual Driver while scooping sample of interest
   - ❑ Release handle, capturing sample inside Soil End Effector
   - ❑ √ Stow Soil End Effector in Sample MRU container

**CAUTION**
Soil samples may leak from end effectors if seal not set

8. Repeat Soil Sampling procedures until desired samples are collected

9. Verify ALL sample IDs with sample container IDs

10. Clean-Up Worksite

11. Stow Hardware
    - ❑ √ All tools stowed and secured in containment bag
    - ❑ Stow containment bag on Rover
    - ❑ √ Tether straps secure on all compartments on Rover



Figure A.16: IV detailed timeline for nominal scenario condition - page 5 and 6.

## EVA – 6S: STAGE EVA – STATION #5 ACTIVITIES (00:35) CONT.

**IV**

14. Confirm each sample is collected and stowed (Record Sample ID with Associated Container ID)

15. Estimate time of departure

16. Compute estimate of minutes behind
(projected minus planned Station #5 end time)

17. Compute estimate of timeline margin

18. How Confident are you in your estimate (+/- min)

19. Systems Check prior to station departure

| Variable | EV1 (CDR) | EV2 (MMP) |
|---|---|---|
| O2 (lbs) | | |
| Pressure (psi) | | |
| EMU Faults | | |
| Water (lbs) | | |

20. Record PET at Departure

**EV1 (CDR)**

GEOPHYSICAL MRU EXPERIMENT (00:35)

14. Clean-Up Worksite
    - ❑ √ MRU Systems on data collection standby mode
    - ❑ √ All panels of MRU are secure and closed
    - ❑ Stow hardware tools in MRU containment bag
15. Stow Hardware
    - ❑ √ All tools stowed and secured in containment bag
    - ❑ Stow containment bag on Rover
    - ❑ √ Tether straps secure on all compartments on Rover
16. Mount rover
17. Verify rover scientific instruments active
18. Verify following in good config prior to commencing translation (00:02)
    - ❑ Seat belts fastened
    - ❑ Cooling
    - ❑ Visors
    - ❑ Glove heaters
    - ❑ √Tools & Tethers clear
    - ❑ √Gloves & HAP
19. Confirm GO for Translate

**EV2 (MMP)**

GEOPHYSICAL SAMPLING (00:35)

12. Mount rover
13. Verify following in good config prior to commencing translation
    - ❑ Seat belts fastened
    - ❑ Cooling
    - ❑ Visors
    - ❑ Glove heaters
    - ❑ Tools & Tethers clear
    - ❑ √Gloves & HAP
14. Active rover from sleep mode
    - ❑ Verify NAV states
    - ❑ NAV RESET "RESET" - "OFF"
    - ❑ Position LGA 020⁰ at Power Up
15. Confirm GO for Translate



## EVA – 6S: FLIGHT NOTES

**Timeline Margin Calculation**

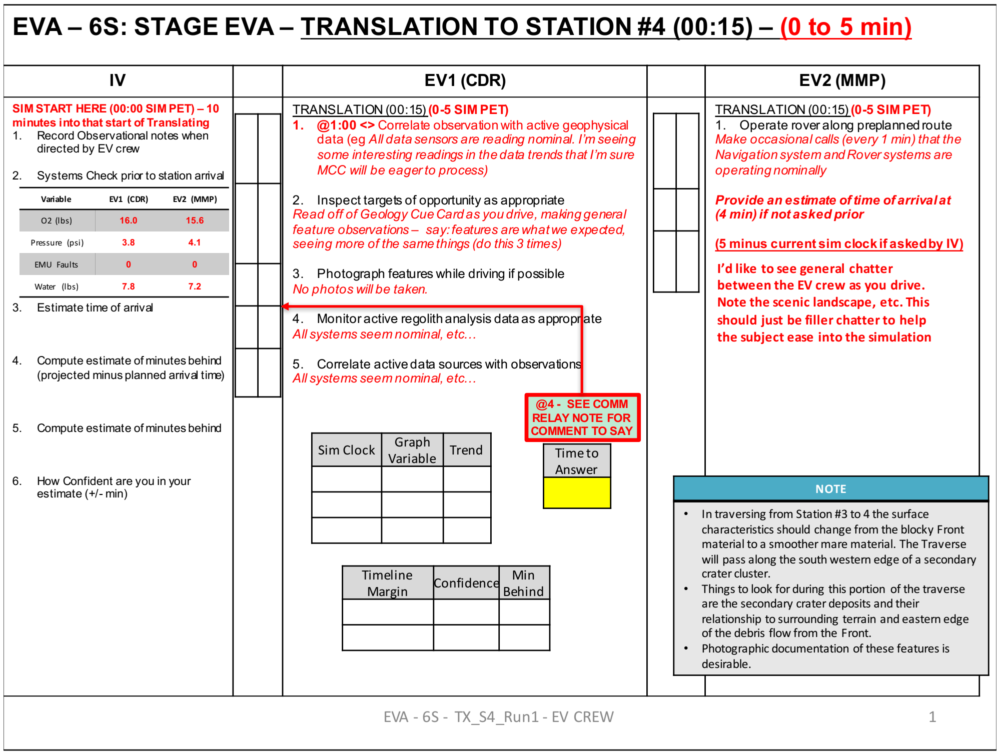
| PET | + ETA | = Pred. PET | - Plan PET | = Min. Behind | | Limiting Resource | - Nominal Time Rem. | = Nominal Margin | - ETA | = Timeline Margin |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |

**Numerical Telemetry Events** / **Graphical Telemetry Events**

| PET | Yellow/Red (Y/R) | Channel | Variable ID | Value (if red) | | PET | Variable | Channel | Trend | Value (if exceed bounds) |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |



Figure A.17: IV detailed timeline for nominal scenario condition - page 7 and 8.



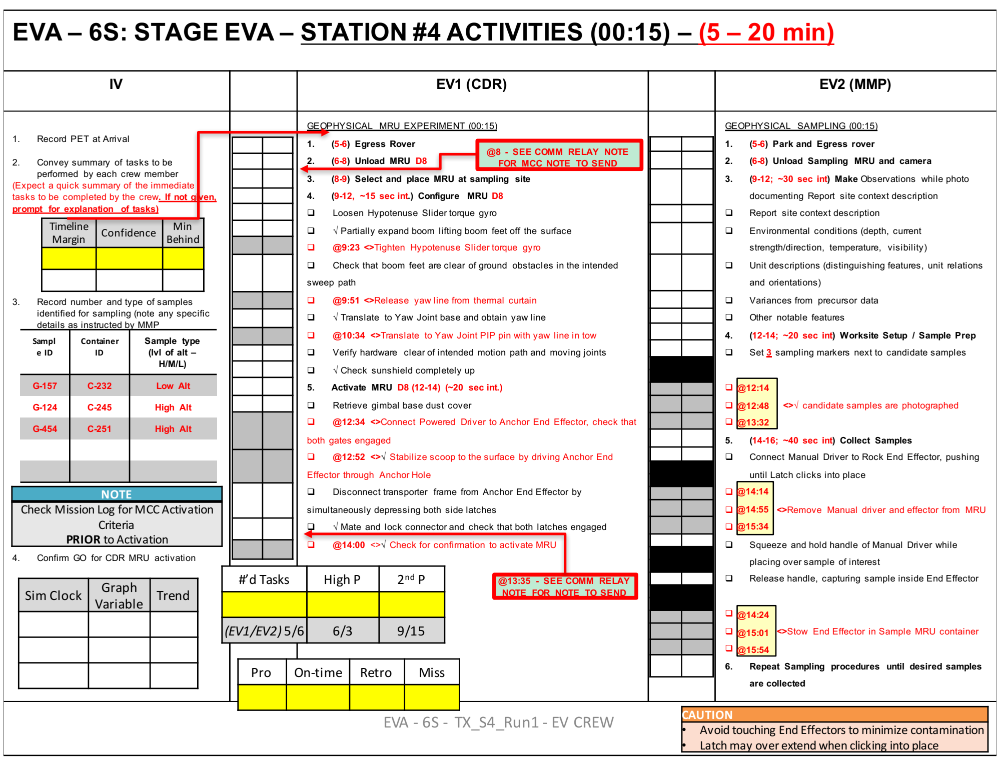
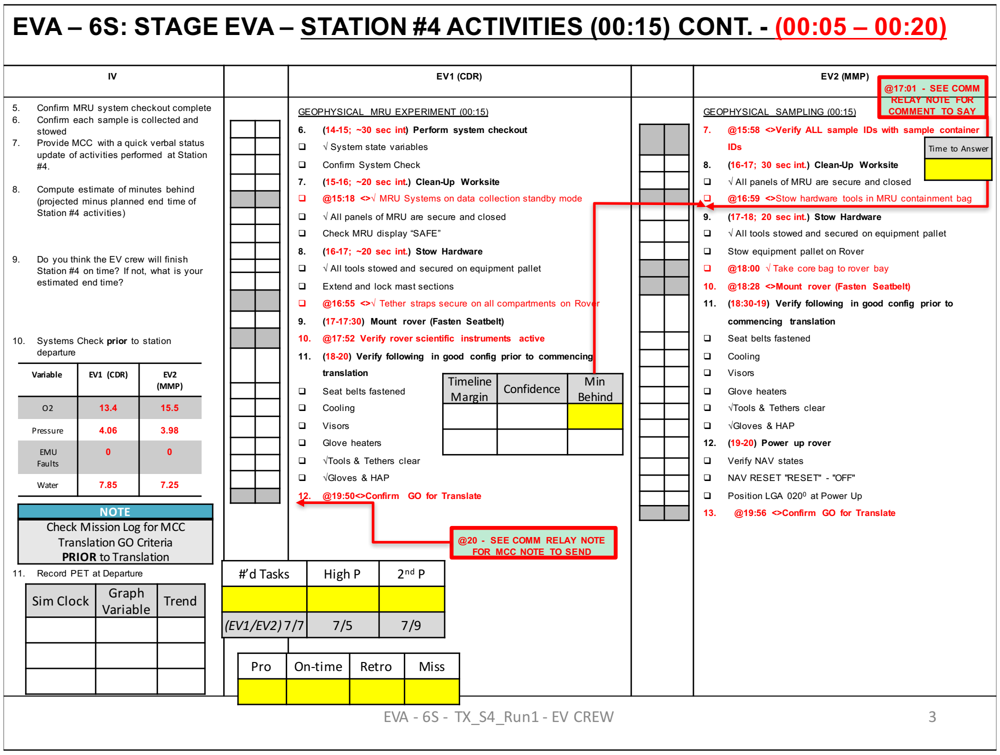




Figure A.18: EV detailed timeline for nominal scenario condition - page 1 and 2.



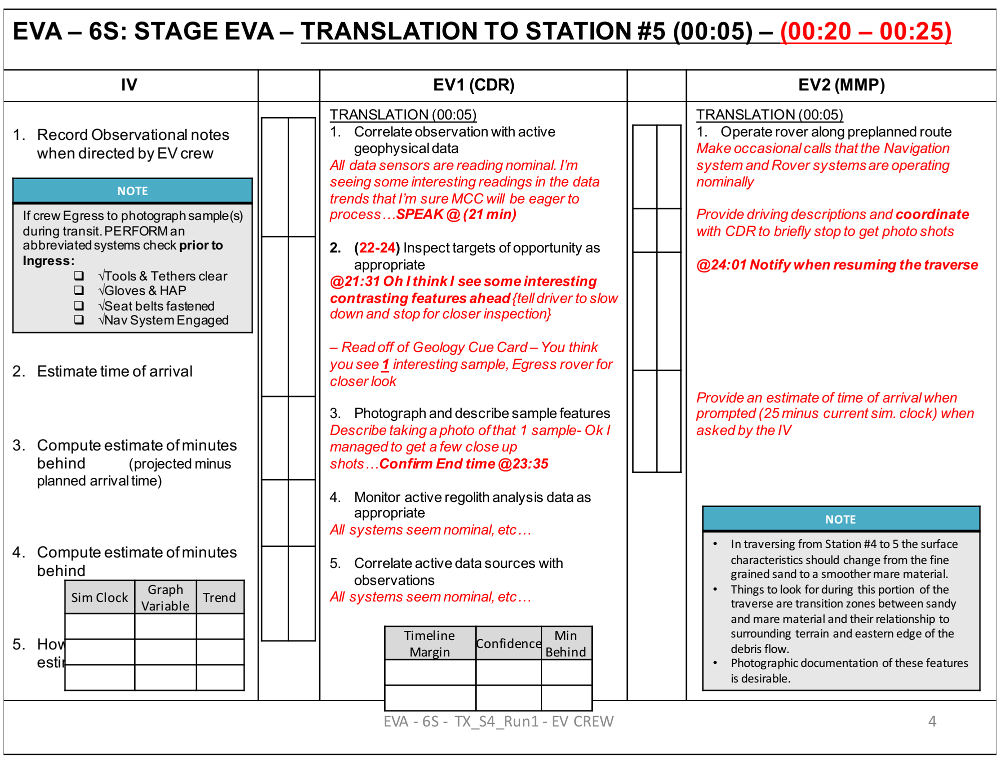
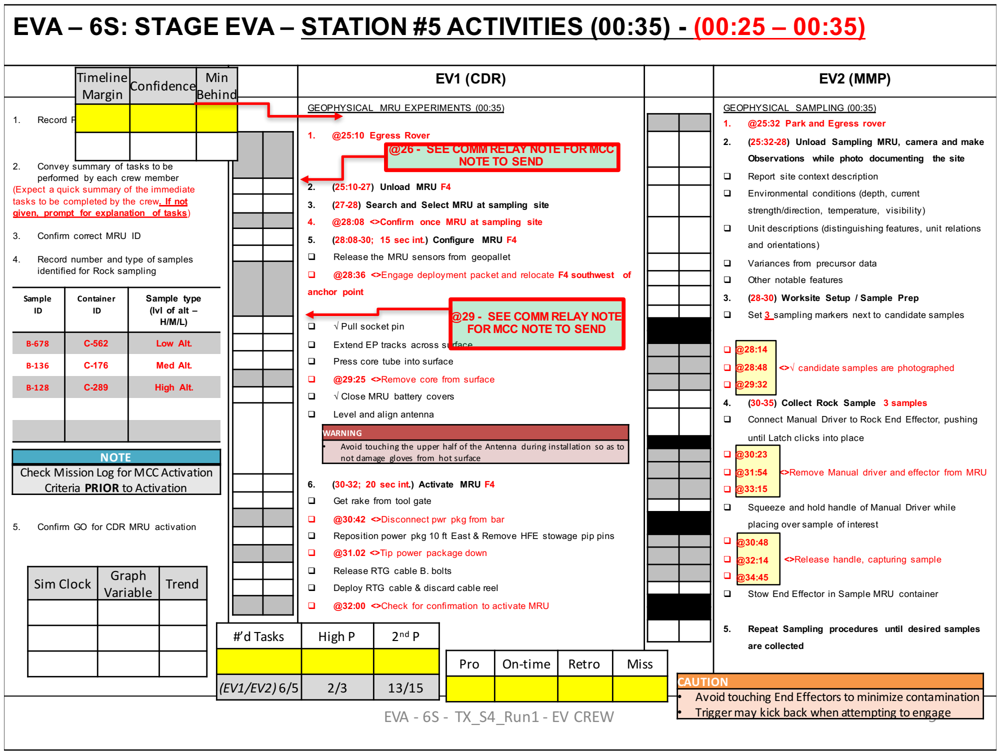



Figure A.19: EV detailed timeline for nominal scenario condition - page 3 and 4.



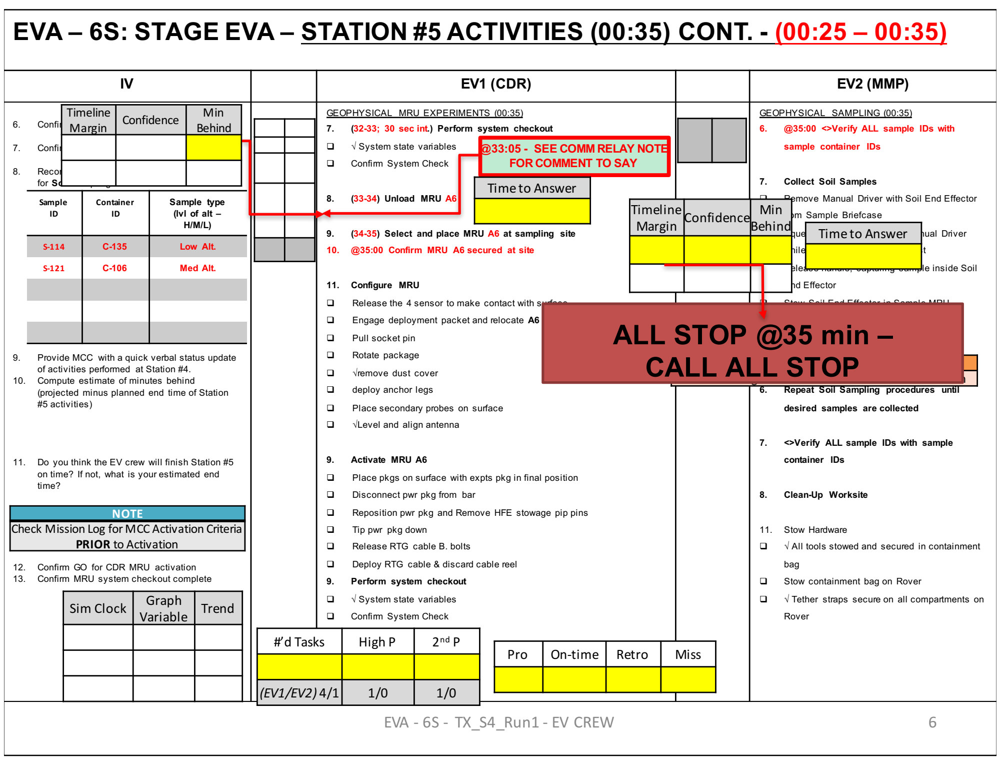




Figure A.20: EV detailed timeline for nominal scenario condition - page 5 and 6.

## Biographical Questionnaire

Please fill out the following biographical data fields

Subject ID

Short answer text

Age *

Short answer text

Major *

Short answer text

How long have you been in graduate school? *

Short answer text

Please indicate any previous work experiences (and durations) that you would say are similar to the tasks you performed during this study (e.g. Military operations or real-time logistics)

Long answer text

Figure A.21: Biographical Questionnaire.

| OPERATOR EVALUATION CRITERIA |
|---|
| **Mission Cognizance** |
| Consistently monitors Mission Log, Telemetry Data and Audio Loops |
| Maintains an awareness of current, pending, and ongoing operations |
| Maintains an awareness of system configurations, and EVA timeline |
| Manages system resources and resolves system conflicts to maintain safety margins and/or meet mission objectives (uses good common sense) |
| **Systems Knowledge** |
| Demonstrates a good working knowledge of procedures and safety constraints in executing activities |
| Applies appropriate judgment with respect to deviations from procedures:<br>o Shows good judgment with respect to developing or requesting deviations from procedures<br>o Provides technical rationale to obtain deviations from Flight Rules and safety constraints<br>o Seeks concurrence to deviations from safety constraints |
| **Problem Recognition and Resolution** |
| Identifies the existence of a problem and notifies appropriate personnel in a timely manner |
| Gathers appropriate data to confirm identity of problem |
| Identifies/executes time-critical responses for crew/vehicle safety |
| If Operator, develops options and recommendations for EV Crew |
| **Console Management** |
| Executes proper console response to given situation, including<br>o Maintaining accurate console logs<br>o Command execution<br>o Practicing routine data scanning and status reporting techniques |
| **Communication** |
| Differentiates information required by: MCC and EV crew |
| Demonstrates, with respect to communication with others, maintenance of appropriate loop |
| Uses appropriate documents to communicate mission status or system status information, including Flight Notes, subsequent shifts, deviations from Flight Rules or procedures, “Chits,” console logs, and weekly/increment planning processes |
| **Attitude and Effort** |
| Provides inputs in a positive, calm, and constructive manner |
| Demonstrates consistency and initiative in representing system requirements to others |
| Demonstrates appropriate level of persistence in problem recognition or resolution, and using all the tools available to perform the correct course of action |
| Encourages maximum effort from others through personal words and actions |

Figure A.22: Intravehicular Operator Proficiency Assessment. Each dimension was ranked on a scale (1-5) with 1 indicating not proficience at all and 5 indicating extremely proficient.

# NASA Task Load Index (TLX)

We are interested not only in assessing your performance but also your experiences in the different conditions. Basically we want to examine you "workload."

Since workload is something experienced individually, it can be difficult to estimate. Because workload may be influenced by many different factors, we would like you to evaluate several factors individually rather than lumping them into a single evaluation of overall workload. This set of six rating scales was developed by NASA. Please read the descriptions of the scales carefully.

Please evaluate the EVA and your experience with the IV workstation by marking each scale at the point that matches your experience. Note that "performance" goes from "good" on the left to "bad" on the right. Consider each scale individually. These ratings are an important part of the experiment and I appreciate your efforts.

Please ask questions if you are unsure.

Today's Date *

Month, day, year

Subject ID *

Short answer text

Run Condition *

- CERT
- Run 1
- Run 2
- Run 3

Figure A.23: NASA TLX Questionnaire - page 1.

### Mental Demand - Description

How much mental and perceptual activity was required (e.g., thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?

### Mental Demand - TLX Score *

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | |
|---|---|---|---|---|---|---|---|---|---|---|
| Low | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | High |

### Physical Demand - Description

How much physical activity was required (e.g., pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?

### Physical Demand - TLX Score *

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | |
|---|---|---|---|---|---|---|---|---|---|---|
| Low | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | High |

### Temporal Demand - Description

How much time pressure did you feel due to the rate or pace at which the tasks or task elements occurred? Was the pace slow and leisurely or rapid and frantic?

### Temporal Demand - TLX Score *

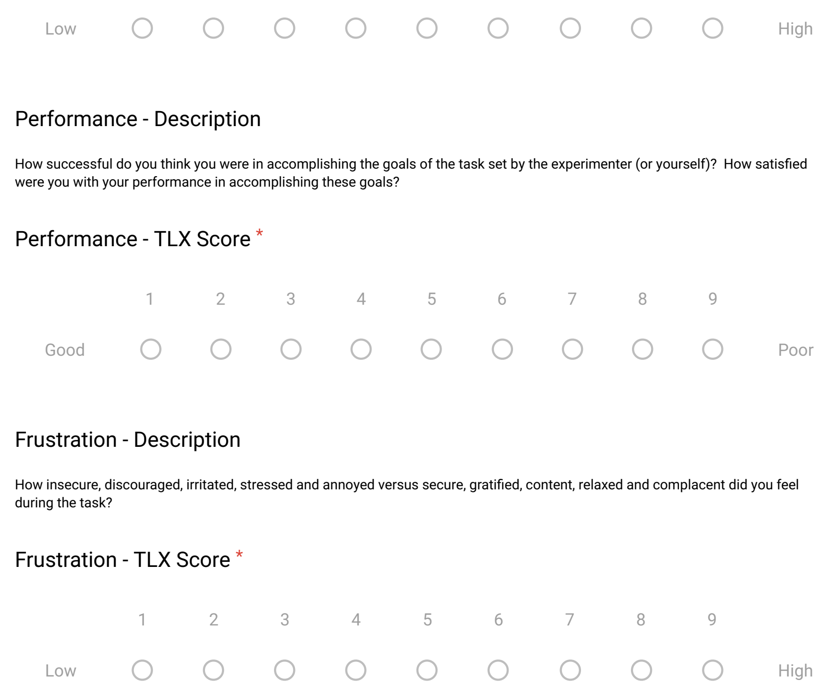
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | |
|---|---|---|---|---|---|---|---|---|---|---|
| Low | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | High |

### Effort - Description

How hard did you have to work (mentally and physically) to accomplish your level of performance?

### Effort - TLX Score *

Figure A.24: NASA TLX Questionnaire - page 2.



Low ○ ○ ○ ○ ○ ○ ○ ○ ○ High

Performance - Description

How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?

Performance - TLX Score *

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | |
|---|---|---|---|---|---|---|---|---|---|---|
| Good | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | Poor |

Frustration - Description

How insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the task?

Frustration - TLX Score *

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | |
|---|---|---|---|---|---|---|---|---|---|---|
| Low | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | High |

Figure A.25: NASA TLX Questionnaire - page 3.

# Cognitive Support Questionnaire

We are interested not only in assessing your performance but also study the cognitive support your received (or not) from the IV workstation. Basically, we want to examine how well the software tools you used during the simulation supported the cognitive demands you experienced.

Since cognitive support is something experienced individually, it can be difficult to estimate. Because cognitive support may be influenced by many different factors, we would like you to evaluate several factors individually rather than lumping them into a single evaluation of overall cognitive support. This set of questions was developed to explore how effective the tools you interacted with were at helping you perform your role as an IV operator. Please read the descriptions carefully. Please answer the prompts to the best of your ability

If you think the question is not applicable, given your experience during the EVA, please select [N/A] for Not Applicable

Please ask if you have any questions

Today's Date *

Month, day, year

Subject ID *

Short answer text

Run Condition *

- ◯ CERT
- ◯ Run 1
- ◯ Run 2
- ◯ Run 3

Figure A.26: Cognitive Support Questionnaire - page 1.

Overall Performance *

| | Significantly behind | behind | on schedule | ahead | significantly ahead |
|---|---|---|---|---|---|
| From a timeline execution perspective, assess the overall state of the EVA timeline progress | ○ | ○ | ○ | ○ | ○ |

Mission Objectives Assessment *

| | None | Some | Half | Most | All |
|---|---|---|---|---|---|
| Assess whether you have achieved the mission objectives for today's EVA timeline | ○ | ○ | ○ | ○ | ○ |

How effective were the support tools in the following aspects: *

| | Not Effective at All | Slightly Effective | Somewhat Effective | Very Effective | Extremely Effective | N/A |
|---|---|---|---|---|---|---|
| Supporting communication and coordination among EVA operators (MCC, IV, and EV crew) | ○ | ○ | ○ | ○ | ○ | ○ |
| Thinking specifically with regard to potential timeline alterations, supporting communication and coordination among EVA operators (MCC, IV, and EV crew) | ○ | ○ | ○ | ○ | ○ | ○ |
| Maintaining awareness of tasks being performed by the EV crew | ○ | ○ | ○ | ○ | ○ | ○ |
| Maintaining awareness of upcoming tasks to be performed by the EV crew | ○ | ○ | ○ | ○ | ○ | ○ |
| Identifying where EV crew members are in the EVA timeline | ○ | ○ | ○ | ○ | ○ | ○ |
| Identifying which segments of the EVA deviated from the planned timeline, if any | ○ | ○ | ○ | ○ | ○ | ○ |
| Identifying which tasks are most critical | ○ | ○ | ○ | ○ | ○ | ○ |
| Assessing implications of delays in EV crew task execution | ○ | ○ | ○ | ○ | ○ | ○ |

Figure A.27: Cognitive Support Questionnaire - page 2.

How effective were the support tools in the following aspects: *

| | Not Effective at All | Slightly Effective | Somewhat Effective | Very Effective | Extremely Effective | N/A |
|---|---|---|---|---|---|---|
| Supporting effective planning of EVA timeline for each EV crew member | ○ | ○ | ○ | ○ | ○ | ○ |
| Providing support for prioritizing your tasks as an IV operator | ○ | ○ | ○ | ○ | ○ | ○ |
| Identifying what are the most limiting consumables for each EV crew member | ○ | ○ | ○ | ○ | ○ | ○ |
| Identifying detrimental trends in the EV crew telemetry data | ○ | ○ | ○ | ○ | ○ | ○ |
| Assessing the timeline margin available, relating the estimated end of the EVA timeline with the most current limiting consumable | ○ | ○ | ○ | ○ | ○ | ○ |
| Identifying potential timeline alterations | ○ | ○ | ○ | ○ | ○ | ○ |
| Supporting effective alteration of EVA timeline | ○ | ○ | ○ | ○ | ○ | ○ |

Please indicate anything about the IV workstation configuration you found particularly useful or detrimental to you performing your role as the IV operator.

Long answer text

Figure A.28: Cognitive Support Questionnaire - page 3.

| Please indicate anything about the IV workstation configuration you found particularly useful or detrimental to you performing your role as the IV operator. |
|---|
| Manual calculations are a huge distraction during operations. Difficult to shift focus between paper and computer (as a corollary, it was very difficult to catch and note telemetry dropouts). Trend graphs are helpful for assessing status. |
| Graphs of suit parameters are easy to read and monitor. Difficult to monitor screen of just raw suit data. Text communication with MCC is helpful/smooth. Performing manual writing/calculation is distracting. |
| The detailed timeline helped me to keep up with tasks and catch errors in the tasks. Knowing that we were generally ahead of schedule helped to relax and make decisions based on workstation info. |
| Having the list of tasks on paper when everything else was on the computer. It would be easier is everything was on the computer |
| Having to synthesize information from multiple sources for the time calculations was quite detrimental to my performance. |
| Switching between paper and the computer was distracting |
| Hand calculations requiring the synthesis of information from multiple sources |
| Hand calculations requiring the synthesis of information from multiple sources is detrimental |
| I think that there is too much to look at consistently. An audio cue for bad data would be nice. Deviations from the average in graphical data should also have an audio cue. Furthermore, it might be helpful for the crew scientist to only detail sample collection procedures once. Comms overlap was sometimes an issue as well. |
| They key challenge as the IV operator was multitasking. Therefore, quick and easy ways to do my tasks are useful. The graphs of the trends on the right were useful to quickly get an idea of what was going on. I liked that the numerical telemetry displays would flash a different color to indicate deviations from "Good", again because it's an easy and quick indication. Likewise, the limiting consumable being a different color was nice. The IM system with MCC was good for sending and receiving messages, although it would be nice if there was a quicker/easier way to indicate that I copy a certain message from MCC, like a keyboard shortcut instead of having to use the mouse. The audio system was very useful, as it was quick and responsive. The paper checklists were good at letting me know what tasks needed to be performed by whom in what order, but it got difficult if the two crew members got out of sync with each other or with me, especially across multiple pages. Some sort of scrolling screen would be more ideal perhaps. As for keeping track of the time, while the formula and tables were easy to understand from a mathematical perspective, actually executing those calculations while trying to do everything else was difficult. A computerized table, where I could just fill in the 3 variables, and it would automatically calculate the rest, would be awesome. Even better would be to somehow integrate it with the task list so that I could have a constant update on this ready for the crew when they ask. Essentially, the manual nature of this calculation coupled with trying to also manually calculate the expected amount of task time left, while doing all the other tasks, was detrimental. |
| I think I just learned how to use the workstation better compared to the CERT run yesterday. |
| Could use the marking of the most vital tasks with something more obvious than the small check mark; maybe a different color/bold font? |
| The fact that I was flipping back and forth between multiple pages was very detrimental. In order to better track the timeline, the fact that that's a manual process and takes a non-trivial amount of time to do the math is also detrimental. The graphs and color coding on the computer screen are useful. |
| Wish there were tones for color changes in data summaries, looking down a lot |
| I just want the display to make a tone to indicate telemetry event. If it can change color, it can make a tone. |
| Still want noise on telemetry errors. |
| Still want noise on telemetry. Also, would be nice if plugin supported margin calculation. |

Figure A.29: Cognitive Support Questionnaire Open-Ended responses for the Baseline DSS prototype - page 1.

| Please indicate anything about the IV workstation configuration you found particularly useful or detrimental to you performing your role as the IV operator. |
|---|
| Calculations were very time consuming to complete along with all other tasks. In comparison to a digital tool, I wasted time calculating the timeline margin for recording purposes, calculating the timeline margin for EV requests, and flipping between pages of EV activities. There was a significant amount of wasted effort here that slowed down my communication of tasks to EV1 and EV2. |
| The calculations were cumbersome and need to be automated. Took a significant amount of time and focus away from critical tasks. |
| The same calculations are cumbersome and take a significant amount of time and focus away from critical IV tasks. I also wanted to note that the simulation is becoming easier out of repetition. If I hadn't had previous experience with Station 4 and Station 5 activities, this workload would be much more difficult to manage. |
| The calculations were especially cumbersome in this simulation. There were a lot of data anomalies and telemetry events to keep track of, and it was extremely challenging to keep up with the calculations here. It was also difficult to flip pages when EV1 and EV2 were not at identical timelines. It was time consuming to keep flipping back and forth between pages. |
| The need to be working on multiple pages at a time was a pain when the timelines got out of sync. Also, having to do a lot of the mental math lead definitely increased a lot of the workload, and probably led to math errors on my part. |
| Math is hard |
| Having to flip between pages to get to different activities made it very difficult to estimate the effects of different changes in the timeline. Tools don't provide support for even the basic mental math needed for timeline calculations, leading to higher probability of mental math errors. |
| The tools are fine when the demand is low, but when both operators were performing separate tasks at different points in the timeline it becomes much more difficult to keep track of the activities and the telemetry and the timeline calculations all at once. |
| Again, the transition periods were not terrible due to lower IV activity, but during the activity phases keeping track of both checklists and the telemetry data and keeping on top of the timeline calculations required a lot of different tasks in working memory. I'm sure I missed some telemetry events even though they were on schedule. |
| Notifications on telemetry are hard to pick up at times |
| The manual calculation was taxing; a calculator might be helpful (even a time-specific calculator application) |
| The yellow highlights on limiting consumable make it particularly fast to find and record that value during timeline margin calculation |
| Gray color on required data entry helps ensure that it is not missed |
| Ability to quickly flip ahead to the next set of tasks was helpful |
| Hand calculations, obviously, are a huge source of error, and the paper system made keeping track of these very difficult. On the digital display, the font and color choices were particularly poor, with the font showing very poor clarity between different numbers/letters, and the harsh color scheme precluded quick scanning of variable status. Lack of audio cues (beyond MCC message) was also problematic, and paper system made consistent visual checks of the display screen difficult to integrate into the workflow. |
| Constantly looking down at papers and recording times limited consistent checks of EV telemetry and other visual warnings. Audio signals for data updates events (.e.g, quite ping every 20 seconds) could be useful, though may also be distracting in its own right. |

Figure A.30: Cognitive Support Questionnaire Open-Ended responses for the Baseline DSS prototype - page 2.

| Please indicate anything about the IV workstation configuration you found particularly useful or detrimental to you performing your role as the IV operator. |
| --- |
| I really liked not having to do simple but distracting math, allowing me to focus on overall EVA management. Would be nice if clicking outside the box did not select the check box (i.e. necessitating an actual click inside the box, perhaps compensated for with a larger check box). Was annoying when clicking to remove an accidental right click menu also selected the task (or sometimes multiple tasks). |
| Very clear at a glance what the major tasks are, and how far behind or ahead we are of the timeline. Telemetry readout are simple and intuitive. No real complaints, nice not to have to do distracting math while trying to manage higher level tasks for EV crew. |
| THIS IS SO MUCH BETTER THAN BEFORE. I cannot stress this enough. At no point was I feeling overwhelmed, and it was easy to recover from a small mistake as an IV operator. A trained monkey could do this now. |
| Still much better than old method. Still much easier. Nice to be able to focus without dividing attention between screen and paper. Much easier on my neck, can just flick eyes between telemetry and the timeline. |
| The coloring of comments/warning is helpful to know what needs to be communicated to the EV crew members |
| When holding shift for Push To Talk and clicking, the client would highlight some of the text, which caused a distraction from performing required tasks and added additional cognitive workload for the IV user |
| Several of the MRU identifiers in the task list did not match the MRU number sent from MCC. This required some extra verbal confirmations with the crew |
| When attempting to remove highlighting caused by holding shift and clicking, there are few places to click that do not activate or deactivate a check box |
| The automatic calculations were very helpful. |
| The clock displaying the current duration of the task would not stay on the screen as I scrolled down to observe the tasks being performed. |
| The warnings and cautions could be placed a little closer to the task for which they are relevant |
| Increase the size/contrast of the high priority task markers |
| It can be difficult to tell if one crew member is falling behind the other crewmember |
| Notifications should have a permanent contrasting color, until they are confirmed by operator |
| The auto-complete of items from sub-items was sometimes distracting, I had to leave a sub-item unchecked even though I'd mentioned it before, to note they hadn't arrived yet. |
| At one point I couldn't remember if I'd copied an MCC reply and couldn't figure out how to check that, since the messages reorder. Otherwise, I only wish there was an "arrive at station" checkbox so the transit wouldn't autocomplete ev2 as I read the info to her. |
| The checklist style of the tasks makes it easy to see what should be done next, and with practice it's becoming easier to pick out the salient parts. The checks next to the "confirmation" items also help in figuring out what should be verified. |
| As I get more used to the interface, the only thing I find I would like is some distinction of key words in the longer procedures (verbs, important nouns) to avoid just reading the whole line. |
| Real-time visualization of the tasks as they were happening would be very effective helping the IV keep up with what the crew is doing. Having a supporting cartoon that was updated as milestones were hit, along with shaded pictures of upcoming tasks, would quickly give the IV good intuition about how to respond without having to spend so much time reading text. These cartoons could also be shown in the Task List to reinforce visual connections. Additionally, having an auto-scroll feature to advance the task list as tasks are completed would reduce approximately 20 % of the clicks needed by the IV. |
| Good interface with vital graphs, earth communication, and task list checkoffs. Need to identify which tasks are iterative, such as sample collection, with a visual marker |
| Good experience overall with vital data, chat interface, and task list check-offs. Visualization reinforcement would be useful, and a visual timeline would help IV plan for the next 2-3 tasks that are on deck. |

Figure A.31: Cognitive Support Questionnaire Open-Ended responses for the Advanced DSS prototype - page 1.

| Please indicate anything about the IV workstation configuration you found particularly useful or detrimental to you performing your role as the IV operator. |
| --- |
| Good experience with vital graphs, chat interface, and task list check-offs. An auto-scroll feature would have been extremely helpful because this EVA seemed longer and more eventful than other EVA's. More events caused me to spend more mental energy and have a slightly increased stress level. Especially during busy moments, an auto-scroll feature would reduce the amount of clicking that I had to perform to keep up with the crew timeline. |
| I really liked the timeline margin updating feature. Perhaps a beep or some other indicator when suit telemetry data is going off nominal could be helpful |
| There could be more detailed expected times for subtasks |
| The slight lag where I have to wait for the incoming MCC message to not be blue anymore before I can click on it to copy it was a bit detrimental, as is the fact that I have to click the message, move the mouse to one Add Note button, and then click a different Add Note button to copy. Just streamlining that whole process would be nice. Other than that, everything else about the workstation is super useful. The fact that I can independently scroll the two EV task lists, the fact that everything is on the computer and I don't have to switch between computer and paper, and most importantly, that all the time behind and timeline margin calculations are done automatically, are particularly useful (oh, and the fact that the one limiting consumable is just displayed, and I don't have to sort through the whole consumables list). |
| It might help to have the iterative tasks be iterative in the checklist, but that is a minor luxury that is not necessary. |
| I like that the MCC window beeps when there's an incoming message; it would be nice if the crew telemetry data window also beeped or gave some audio signal when there were sudden changes. Same story for the red exclamation mark; if that could be accompanied by an audio signal, that would be even better. In sum, all the visual signals are good; pairing them with short audio signals would be even better. I still like the streamlining of the most limiting consumable display, although I just realized that it doesn't tell me what the limiting consumable is for each crew member, just the one that is the most at risk; it would be nice to know the most limiting one for both, so maybe have 2 lines for Lim Cons instead of 1, and just highlight the one that's worse off. It would also be nice to have the allotted time for each task, instead of just for the activity as a whole, but at this point, I'm just nitpicking; this whole setup is actually very effective in telling me what each crew member is doing and where we are in the timeline. |
| I still really like that everything is on the computer and that I can easily look between the three windows. I'm getting more used to dealing with the Copying mechanism for communicating with MCC. I definitely like the independent scrolling for each EV and the automatic math for the time behind and timeline margin; these two are definitely my favorite aspects. Two things that might be helpful would be if 1) the red and yellow warning boxes were next to the sub-task to which they applied instead of just being at the bottom of the task box, and 2) if there was a little less spacing between steps, so I could see more steps on the screen at the same time, although I was able to mitigate this somewhat by being more on top of scrolling to keep up with where the EVs were at. |
| This run, I found it particularly useful that the sub-tasks were all grouped under a task, and I could just check off the whole task, and it would automatically check off all the sub-tasks underneath it, since this saved time and enabled me to catch up a bit when things went wrong. As always, the automatic math for time behind and timeline margin is sooo helpful! |
| I really enjoyed the interactive checklist and not having to do time math |
| Multiple checkboxes of iterative tasks would be nice |
| The detailed task view is very helpful for following along with timeline tasks. It is still somewhat difficult to effectively monitor crew telemetry data and switch back and forth. |
| Detailed task view is very helpful for following along with the timeline. Ability to click once tasks are complete is simple and effective. |
| Even though we were significantly behind in the timeline, it was difficult to know what, if any, alterations could be made to help catch up. Easy to assess how behind we were, but would be nice to be able to help catch up. |
| Detailed task view was again very helpful for following along with the timeline. Generally, it is easy to read and view upcoming tasks so that can keep the crew on track.<br><br>Graph view of crew telemetry is generally easy to use / spot trends - once you are accustomed to it. |
| Telemetry plot screen could be simplified and compressed a bit for less visual "busyness". For example, since all plots share the same time axis, space could be saved by grouping telemetry together and sharing one time axis. This might allow increased size of the plots for easer quick inspection of the telemetry data.<br><br>Mission log flow could be enhanced by grouping together individual messages and acknowledgements. Out-of-order confirmations made it confusing (at a glance) to determine which messages have been confirmed. |
| A reminder to confirm MCC messages (in addition to the arrival ping) would be useful, especially if some time (e.g., 60 seconds) pass without confirmation of the message. |

Figure A.32: Cognitive Support Questionnaire Open-Ended responses for the Advanced DSS prototype - page 2.

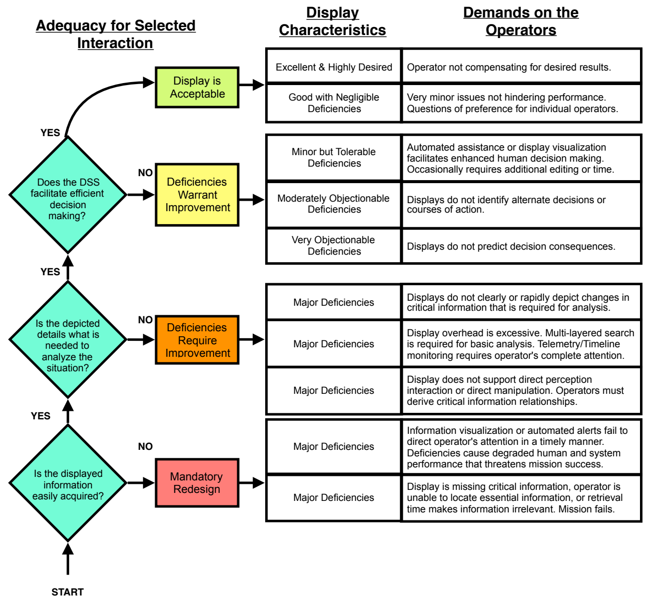



Figure A.33: Interaction Assessment Questionnaire.

| Feel free to indicate any specific aspects of the IV workstation you found warrant improvement |
|---|
| Displayed information is relevant but it's very difficult to keep up with it in a timely manner and slowed down my performance tremendously. |
| Paper format cumbersome |
| Essentially automating some of the tasks that I had to do manually, like the time remaining and margin calculations, and integrating that better with the task list, would be an improvement. I could still use these to identify alternate decisions/consequences, even if it was a bit cumbersome, so I picked the first option for this question. |
| Information was conveyed clearly, would be nice to have audible alert tone |
| It was difficult to keep looking down at the tasks in front of me, to the left side for the timeline estimates, and scanning the vital graphs and data summary. Dividing my attention between 6 different sources contributed to significantly slower reaction time for events and slower communication of tasks to EV1 and EV2. |
| Flipping back and forth between pages was difficult. It was very cumbersome to perform the calculations, which took away valuable time and focus from other IV tasks. Also, there were too many notes that needed to be taken by the IV, which also took away time and focus from other tasks. |
| Computing the timeline margin and minutes behind was more human-intensive than it should have been. The amount of data shown was somewhat overwhelming and didn't really support these tasks. |
| Definitely harder than Marvin the Martian |
| There is a lot of information thrown at the user, I'm pretty sure I didn't read half the extraneous panels at all. I would have liked to have seen some estimate of the timeline margin and time behind to provide a check for my mental math, which always proved the most time-consuming part and took away attention during critical activity phases of the EVA. |
| I'm not sure it risked mission failure. There were delays. High priority information was not immediately obvious and could be difficult to find |
| calculating timeline margin and minutes behind helped me to stay more aware of it, but it detracted significantly from tracking task progress |
| More important data needs to be highlighted visually. Important cues and events need both audio and visual components. |
| Visualization of data is still poor (text, color, layout, etc.), but a basic level of familiarity can be gained from repeated usage. In a time-pressed situation, however, it is still highly likely that key information would go unnoticed. |
| Mostly the lack of being able to monitor the screens while checking the progress of the EV team during busy portions made it hard to see if there were any issues that needed to be noted. Even MCC messages sometimes seemed hectic to respond to if the EV team were doing a lot of things simultaneously. |

Figure A.34: Interaction Assessment Questionnaire Open-Ended responses for the Baseline DSS prototype.

| Feel free to indicate any specific aspects of the IV workstation you found warrant improvement |
|---|
| Mostly acceptable, except for generous hitbox on selecting task completion. |
| The automatic computation of the timeline margin and delay alone is a vast improvement. Although the math is trivial, things slip though the margins when attention is divided. I don't think I missed nearly as many telemetry events, and was able to respond faster to changes in telemetry trends. Also, I was not having to ask EV members to stop and wait while I caught up. Any mistakes were easily rectified automatically, and did not significantly encumber my mental bandwidth for continuing with mission operations and prevented additional EVA delays from IV operator side. Freed up mental capacity to monitor MCC channel and confirm communications in a more timely manner than previously. |
| Moving the star automatically was helpful to ensure tasks weren't missed or marked completed prematurely |
| Sometimes not sure how exactly important it is to check things off. There are times when I can confirm things with the EVs but times when they move on or I miss confirmation. The high priority items are useful to help id which ones are like have to have done. |
| Biggest challenge was the shift key for Push to Talk causing highlighting. I tended to select tasks as complete as I was holding PTT to talk to the crew, so this happened quite frequently |
| I think the fact that each of the sub tasks can be checked off but are not required to be checked off is good. There are times when I can't catch everything being said over the comms or just forget to mark something as done and it is nice to be able to just click the high level activity and mark it as complete to keep the star in the right place. The only bug which was kinda annoying was at times if you click while holding the shift for comms a large portion of the screen gets highlighted. I wasn't sure if this might cause a problem or not the first couple times it happened but I don't think it does. |
| The different levels of activity could have been more clearly indicated, maybe with different colors. Sometimes, I would have to scroll to find the current location of the star, and it would have helped to have a little indicator on the scroll bars as to where Marvin's star was. |
| A video feed of each EV would be very helpful, so they wouldn't have to describe what they are doing. Depending on how much I needed to scroll the two windows up and down, sometimes the expected duration and current duration would be hidden. It could be more clear at which level the hierarchy of boxes was referring to; maybe different colors could be used to make this clear. Same thing for the multiple stars that were displayed. Sometimes I would have to scroll to find Marvin's star, and it would have been helpful to have a little indicator on the scroll bar as to where I could find it. Also, the task checklist did not update with deviations in the tasks, such as MRU change requests. It was up to me to remember these changes. |
| Blue and Green graphs can be difficult to distinguish |
| Variety of notifications can be difficult to apply in the moment - e.g. new MCC notifications blend with other existing messages that cause items to be overlooked. Where are the falling behind schedule numbers coming from? Who is actually falling behind? Particularly when crew are executing station activities - one is ahead and one is behind - it would be nice to know who I should focus more attention. |
| The auto-complete feature propagating up from sub-tasks might be a personal issue for me. Also, the individual items in the checklists might be rewritten to emphasize the salient parts I should communicate (verbs, important nouns). |
| Just the few nit-picky things: bolded important words, an added item to the traverse for confirmed arrival to avoid auto-complete too early. |
| Good graph readouts for EV vitals. Good chat interface between IV and Earth. Good task list organization and task check-off interface. Improvements could be auto-scroll feature and task visualization |
| The graph displays were good and it was easy to view/analyze them. The mission log was effective at communicating information and the beeping sound was also effective. The task list check-off was easy to interface with, but an auto-scroll feature would have helped reduce the amount of clicking I had to do to advance the timelines of both EV1 and EV2. This would safe mental energy during particularly busy moments. |
| I liked the clean layout for the tasks, complete with checkboxes |
| I liked the timeline margin updates |

Figure A.35: Interaction Assessment Questionnaire Open-Ended responses for the Advanced DSS prototype - page 1.

| Feel free to indicate any specific aspects of the IV workstation you found warrant improvement |
|---|
| I definitely appreciated the automatic timeline math. That was probably what stood out the most. I also appreciated the streamlining of the info; I wasn't overloaded with a bunch of data and had to pick out what was relevant (e.g. limiting consumable). The fact that everything was on the computer was also highly acceptable. And the independent scrolling for the two EVs was great. There were 2 minor issues: 1) copying MCC is a bit tricky, but I did eventually learn how to do it a bit more efficiently, and 2) I want EV2 to be able to continuously talk and have her observations be recorded on a separate channel without fearing that EV1 or myself talking simultaneously would mess that up. |
| The mouse scroll bar did not always register that I was trying to scroll because it was too slick. |
| All the info was there in one place on the computer screens and easily accessible. Since the audio communications had issues, the visual display definitely compensated for that and allowed me to catch up, especially by letting me check off entire tasks and automatically checking off the sub-tasks. Crew telemetry is clear, love the individual scrolling for the two EV task lists, the automatic math for timeline margin and time behind is totally the best, and the communication with MCC, although it took some getting used to, is still pretty good. |
| I enjoyed not having to do time math. |
| Not sure having to scroll both crew timelines separately is always the easiest. It works for when timeline is proceeding differently for both, but could be helpful to be able to "sync" the scroll more easily with some kind of shortcut. Would also be nice (my preference) to highlight the current task a little more (and de-emphasize completed tasks / upcoming tasks. The text is grayed out which is helpful, but would help to focus my attention if the boxes around the text were also grayed out.<br><br>It was very easy to manage and understand timeline margin thanks to the automatic calculations.<br><br>Still a bit hard to synthesize important info from crew telemetry display. Found that scanning this screen distracted me |
| Telemetry graph view: a lot to digest at first, but once accustomed to it, it is fairly easy to see trends through a quick scan.<br><br>MCC text comm system: Generally works well. A bit hard to keep track of what messages I have confirmed and what I haven't. Would be nice if the confirmed message got highlighted in some way. Then, it would be easy to tell which messages I haven't yet seen. Also, would be helpful to have some reminder, or some means, to remember to communicate lower priority messages (like camera filter information) to the crew. As is, it was easy to forget to communicate MCC response to that type of question back to the crew.<br><br>Detailed task view: Generally works quite well. Easy to follow along with current tasks and see upcoming tasks. Would prefer to change highlighting to augment current display, e.g. gray out boxes (in addition to text) for completed tasks; emphasize box of current task more (in addition to star); de-emphasize upcoming tasks a little. All of these are |
| Audio tones, visual indicators, and other interface properties could be tweaked by the operator for their preference and to maximize alertness to changes. For example, I would like the timing information at the top to be a larger font size and bolded for easier quick inspection. |
| Options for timeline deviations (including estimated EVA timeline impacts) would be useful. |

Figure A.36: Interaction Assessment Questionnaire Open-Ended responses for the Advanced DSS prototype - page 2.

# APPENDIX B
# PUBLICATIONS

## B.1 Published Articles

### B.1.1 Journal Articles

1. Feigh, K.M., **Miller, M.J.**, Bhattacharyya, R.P., Ma, M., Krening, S., Razin, Y., (2017) "Shifting Role for Human Factors in an 'Unmanned' Era," *Theoretical Issues in Ergonomics Science*, DOI: 10.1080/1463922X.2017.1328713

2. **Miller, M.J.**; McGuire, K.M.; and Feigh, K.M., (2016) "Decision Support System Requirements Definition for Human Extravehicular Activity Based on Cognitive Work Analysis," *Journal of Cognitive Engineering and Decision Making*, October 2016. DOI: https://doi.org/10.1177/1555343416672112 [Focuses on Chapter 3 content]

### B.1.2 Conference Papers with Podium Presentations

1. Beaton, K., Chappell, S.P., **Miller, M.J.**, Lim, D.S.S., and Abercromby, A. (2017). "Extravehicular Activity Operations Concepts under Communication Latency and Bandwidth Constraints," IEEE Aerospace Conference, Big Sky, Montana,
DOI: http://dx.doi.org/10.1109/AERO.2017.7943570

2. Deans, M., Marquez, J.J., Cohen, T., **Miller, M.J.**, Deliz, I., Hellenius, S., Hoffman, J., Lee, Y.J., Norheim, J., and Lim, D.S.S., (2017). "Minerva: User-Centered Science Operations Software Capability for Future Human Exploration," IEEE Aerospace Conference, Big Sky, Montana
DOI: http://dx.doi.org/10.1109/AERO.2017.7943609

3. **Miller, M.J.**, Coan, D.A., Abercromby, A. F.J., Feigh, K.M., (2017). “Design and Development of Support Systems for Future Human Extravehicular Activity,” 55th AIAA Aerospace Sciences Meeting, AIAA SciTech Forum, (AIAA 2017-1444), DOI: http://dx.doi.org/10.2514/6.2017-1444

4. **Miller, M.J.**, Claybrook, A., Suraj, G., Feigh, K.M., (2016). “Operational Assessment of Apollo Lunar Surface Extravehicular Activity Timeline Execution,” AIAA SPACE 2016, SPACE Conferences and Exposition, (AIAA 2016-5391), DOI: http://dx.doi.org/10.2514/6.2016-5391

5. **Miller, M.J.**, Lim, D.S.S., Brady, A.L., Cardman, Z., Bell, E.R., Garry, W.B., *et al.* (2016). “PLRP-3: Conducting Science-Driven Extravehicular Activity with Communications Latency,” IEEE Aerospace Conference, Big Sky, Montana, DOI: http://dx.doi.org/10.1109/AERO.2016.7500643

6. Chappell, S.P., Beaton, K., **Miller, M.J.**, Halcon, C., Gernhardt, G., and Abercromby, A. (2016). “NEEMO 18-20: Analog Testing for Mitigation of Communication Latency during Human Space Exploration,” IEEE Aerospace Conference, Big Sky, Montana, DOI: http://dx.doi.org/10.1109/AERO.2016.7500717

7. **Miller, M.J.**, McGuire, K.M.; and Feigh, K.M., (2015) “Preliminary Work Domain Analysis for Human Extravehicular Activity,” (Vol. 59, pp. 11-15). Presented at the Proceedings of the Human Factors and Ergonomics Society Annual Meeting. Los Angeles, CA, DOI: http://doi.org/10.1177/1541931215591003

8. **Miller, M.J.**, McGuire, K.M.; and Feigh, K.M., (2015) “Information Flow Model of Human Extravehicular Activity Operations,” 2015 IEEE Aerospace Conference, Big Sky, Montana, DOI: http://dx.doi.org/10.1109/AERO.2015.711894

### B.1.3 Technical Reports

1. **Miller, M.J.**, Claybrook, A., Greenlund, S., Marquez, J.J., Feigh, K.M., (2017). "Operational Assessment of Apollo Extravehicular Activity," NASA/TP-2017-219457

### B.1.4 Presentations (Only)

1. **Miller, M.J.**, McGuire, K.M., Feigh, K.M., (2017). "Decision Support System Development for Human Extravehicular Activity: Designing and testing within Mars surface operational environments," Poster Abstract 17404, NASA Human Research Program Workshop, Galveston, TX.

2. **Miller, M.J.**, (2016) "Operations Support System Development for Future EVA," Extravehicular Activity Technology Workshop, Houston, TX, September 13-15, 2016

## B.2 Planned

### B.2.1 Journal Articles

- **Addressing the Envisioned World Problem: a case study in human spaceflight operations**. Focuses on Chapter 3, 4, & 5 with an emphasis on practical considerations for practitioners addressing the envisioned world problem. Planned for *Theoretical Issues of Ergonomic Sciences*.

- **Decision Support System Evaluation for Envisioned Human Extravehicular Activity**. Presents the human in the loop simulation results to evaluate the two decision support systems as provided by Chapter 5 & 6 content. Planned for *Human Factors* or *Journal of Cognitive Engineering and Decision Making*.

- **Next-Generation EVA Operations Needs**. Situates the findings of this thesis more broadly among the scientific community to identify and establish meaningful pathways for future DSS development within the EVA work domain. Planned for *T.B.D.*

Focuses on Chapter 7 content and insights obtained from the NASA analog fieldwork in Chapter 5.

- **BASALT Special Issue Journal** (2017) I will be a coauthor on numerous special issue journal papers related to the EVA operations and technology development within the BASALT program. Accepted for publication in *Astrobiology*

B.2.2 Technical Reports

- **Miller, M.J.**, Claybrook, A., Greenlund, S., Hutchinson, C., Jones, C., Bates, K., Gilmartin, M., Yavari, E., Sajid, S., Feigh, K.M., (2017) Human-in-the-loop Simulation and Results of Mars Surface Extravehicular Activity. To be submitted as a GT technical report that provides a full description of the simulation, its artifacts, and a full release of experimental data (with analysis code written in R). Focuses on Chapter 5 and 6.

B.2.3 Conference Papers with Podium Presentations

- Suraj, G., **Miller, M.J.**, Claybrook, A., Feigh, K.M., (2017). "Operational Assessment of Apollo Lunar Surface Extravehicular Activity Metabolic Rate," accepted for oral presentation at 2017 AIAA SPACE and Astronautics Forum and Exposition. This manuscript is a companion paper to the NASA technical report recently published that summaries Apollo Lunar surface EVA operations both from a life support system and timeline execution perspective. This paper focuses on quantifying the variability exhibited in metabolic rate and consumables usage during Apollo EVA.

- **Miller, M.J.**, Pittman, C.W., Feigh, K.M., (2017) "Next-Generation Human Extravehicular Spaceflight Operations Support Systems Development" Presents the technical specifications of the advanced DSS design and frames current capabilities within the context of additional envisioned capabilities. Focuses on Chapter 4 & 5 content. Accepted for oral presentation and sponsored by NASA as a NASA delegate at the 68th International Astronautical Congress in Adelaide, Australia, September 2017.

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# VITA

Matthew James Miller was born March 11, 1989 in Glasgow, Scotland. His family immigrated to southeast Georgia, USA in 1994. He graduated from Camden County High School in Camden County, Georgia in May 2007 and subsequently enrolled at the Georgia Institute of Technology where he obtained a Bachelor of Science degree in aerospace engineering with highest honors and a cooperative distinction in 2012.

During his undergraduate tenure, Matthew participated in the cooperative education program at ATA Engineering, Inc. within the vehicle design and fluid dynamics groups. While at ATA Engineering, he supported finite element modeling and computation fluid dynamic simulations for a variety of aerospace related projects including Mar Science Laboratory hardware, NASA Orion Components, and Military and Entertainment industry equipment.

Following a summer internship at the Aerospace Corporation as an interm member of the technical staff, Matthew returned to Georgia Tech in the Space Systems Design Lab under advisement of Dr. Robert D. Braun. In December 2014, he received his Master of Science degree in aerospace engineering. His master's project title was "Supersonic Inflatable Aerodynamic Decelerators for use on Sounding Rocket Payloads" which was in collaboration with the Charles Stark Draper Laboratory.

For his Ph.D. research, Matthew worked under the advisement of Dr. Karen M. Feigh within the Cognitive Engineering Center at Georgia Tech. His research was supported by the NASA Space Technology Research Fellowship and involved the application of cognitive systems engineering and human-subjects studies to design decision support systems for future human extravehicular activity operations. From 2015-2016, he served as the Vice President of the Graduate Student Body at Georgia Tech, responsible for advocating on behalf of over 9,500 graduate students, running the Graduate Senate and overseeing the allocation of a \$5.1M budget. He has earned multiple awards, including the NASA Space Technology Research Fellowship, Georgia Tech President's Fellowship, a GVU Foley Scholar Finalist, and served as a NASA-sponsored delegate to the 2017 International Astronautical Congress. He is involved in numerous NASA analog research programs as a member of the EVA operations team and serves as a Session chair to the IEEE Aerospace Conference.